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ALTERNATIVE HYPOTHESES FOR CHANNELED SCABLAND. I

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ABSTRACT

This paper begins with a summary statement of the features of scabland and of the writer's explanation of their origin. In the body of the paper, various criticisms and suggestions are considered in the light of significant field data. Revision of some of the writer's ideas is indicated. The second half of the paper deals with the question of simultaneous development of all channels of the scabland pattern and with proposed tests of the writer's hypothesis.

Since 1923 the writer has published several papers describing the assemblage of exceedingly peculiar erosional and depositional forms found only on the Columbia Plateau in Washington and farther downstream along the Columbia Valley. In every paper he has urged that the only adequate explanation for this assemblage is a very great but very short-lived discharge of glacial water from the Cordilleran ice sheet. Since this interpretation is wholly without precedent in geological literature it has been received by many with considerable reservation. Since there seemed to be no possibility of producing such a flood by any known causes of glacial ablation, definite skepticism has arisen in some quarters. Had the writer's insistence ceased here, the matter might have rested at this stage, but continued assertion has evoked suggestions in print looking toward other explanations for the phenomena. This paper attempts to show

to what extent the alternative explanations can be used. It is based largely on new data and new kinds of data collected during a subsequent field season.

A brief statement of the flood hypothesis and the nature of the evidence for it, as presented for criticism early in 1927, is here reprinted.[1]

That part of the Columbia Plateau which lies north of Snake River in Washington bears a remarkable system of erosional and depositional land forms. They are extraordinary in their magnitude, in their extent and distribution, and unique in their relationships. Running water is generally conceded to have caused them, but the unparalleled results indicate unparalleled conditions under which it acted.

The channeled scablands constitute the erosional part of the record. They cover almost 2,000 square miles, about one-sixth of the area of this part of the plateau. They are elongate tracts, oriented with the gentle dip slope of the underlying basalt flows, mostly bare rock or with a thin cover of coarse basaltic rubble, commonly with canyons in them, and are bounded by steep slopes of the deep loessial soil of the plateau. They constitute a curious anastomosing pattern, the down-dip convergences inherited from an earlier normal drainage pattern and the divergences, equally numerous, produced by crossing of divides of this older pattern. There are hundreds of tracts of the higher loess-covered areas in the scablands, from a fraction of a square mile to many townships in area, all discontinuous and bounded by the scabland areas. The steep marginal slopes in loess are in striking contrast to the gentle slopes of the older drainage pattern surviving within each isolated loessial tract. Canyons in the scablands are multiple and anastomosing, amazingly so in some tracts; deep canyons and shallow ones uniting and dividing in a labyrinthine fashion about bare rock knobs and buttes unlike any other land surfaces on the earth. Certainly but few of these canyons are inherited from the older pattern.

The scabland drainage was discharged from the northern glaciated portion of the plateau through ten openings into the loess-covered area and led thence by nearly one hundred different routes of varying lengths to nine discharge ways into Snake and Columbia rivers on the south and west. The canyon plexus is the most striking feature of the scablands and probably is most significant of conditions of origin. These canyons are interpreted as channels, not valleys, hence the term "channeled scabland."

The depositional land forms associated with channeled scabland are chiefly great mounded masses of little-worn basaltic gravel. They occur on the down-gradient side of eminences and in other protected places in the scablands, and in the Snake and Columbia valleys below the entrance of the scabland drainage

[1] From *Journal of the Washington Academy of Sciences*, Vol. XVII, No. 8 (April 19, 1927), pp. 200–203.

routes. They are not eroded forms, they possess aggradational slopes, and they inclose depressions or by their position aid in inclosing depressions between themselves and adjacent rock walls. All attempts to interpret them as dissected remnants of terraces or originally continuous gravel deposits have failed. They are gravel bars of huge size.

A brief summary concerning the more significant features and relationships follows.

Canyons of the scablands.—Largely channels of huge rivers, eroded during the Spokane epoch.

A. *Rock basins in the canyons.*—Thousands of them. Commonly elongate with the canyons, generally constituting the canyon floor. Lengths as great as 8 miles, depths as great as 200 feet. Some canyon floors essentially a series of rock basins. Formed by large vigorous streams plucking the columnar basalt. In no other way can most of these basins be explained. Some are potholes at the foot of extinct waterfalls.

B. *Plexus grouping of canyons.*—Occur on crossings of divides of the older drainage pattern, the four largest groups ranging from 6 to 10 miles wide. Developed subfluvially like the high-water anastomosing channels of the present Columbia at the Dalles. Alternative explanation demands a remarkably braided pattern of an eroding stream, with narrower strands in many cases cutting deeper than broader ones.

C. *Cataracts.*—Hundreds of extinct waterfalls, many of which during recession became wider, several 2–3 miles wide. Unless the record of very large streams, they should show the "horseshoe" concentration from any initially great width.

Areas surrounded by the channeled scabland tracts.—Residuals of a once continuous loessial cover, with maturely eroded drainage ways. One hundred to 200 feet of loess removed over large areas.

A. *Aligned scarps of loess facing the scablands.*—Slopes 30°–35°. The bluffs left by undercutting of streams whose width was that of the adjacent scabland, from ½ to 15 miles. They truncate minor valleys of the older drainage pattern.

B. *Small isolated loessial hills on the scabland.*—Slopes as above indicated, with "prows" pointing up the scabland gradient. Some are miles from any other loess. Others, in groups, record abrupt introduction of a large volume of water which simultaneously entered several of the pre-Spokane drainage ways and eroded them to bed rock, leaving these remnants of the former divides.

Trenched divides.—Several remarkable cases where a canyon plexus has three or four closely spaced rock-basined gashes 200–400 feet deep across a divide, yet only one case where one of them cut deeply enough to divert subsequent drainage. Water must have been 100–300 feet deep above preglacial valley bottoms on the north to have crossed. No piracy nor headward erosion nor local drainage has been responsible. Good evidence that no post-Spokane uplift has occurred in these places.

Deposits on the scabland and in Snake and Columbia valleys.—Discontinuous originally. Their features clearly record actual building of each individual deposit. Any explanation must start with this.

A. *Gravel chiefly.*—Pebbles little worn, 90–99 per cent basalt, unweathered.

B. *High deposits*, above brink of canyons 400 feet deep and at foot of loessial scarps, yet identical with other deposits down in the canyons.

C. *Bar forms*, undissected, foreset bedding conforming to slopes where required by this hypothesis. Associated depressions as much as 50 feet deep where vigorous eddies existed. Some bars, 20–100 feet high, blocked subsequent drainage.

D. *Deltaic bar*, 5 miles long and 200 feet thick in Snake and Tucannon valleys, with foresets dipping up these valleys from point of entrance of scabland stream. In striking contrast with Snake River gravels immediately upstream, which are in 60-foot terraces, dissected and with large alluvial fans built out on them, and are composed of 90–95 per cent non-basalt, well-rounded gravel.

E. *Quincy structural basin.*—More than fifteen townships covered with basaltic gravel in terrace-like and mesa-like forms. Channeled canyons tributary to and distributary from this settling basin. The forms, however, are bars, as field study has amply demonstrated. No interpretation as terraces will account for many significant relationships.

Anastomosis of entire scabland tract on the plateau.—Contemporaneous occupation of all scabland routes seems indicated. No evidence on glaciated tract of marginal drainage to supply, in turn, any one or two of ten entrances to the scabland during any conceivable shifting of ice edge. All channels seem to have headed on margin of the glaciated tract. Anastomosis due to the huge volume of glacial water and the abrupt introduction, thus flooding a multitude of minor drainage ways of the plateau and crossing a multitude of minor divides. Insufficient time for erosion of a few adequately capacious spillways. Debouchure into Snake and Columbia valleys at very different levels, indicating varying depth of different channel ways and a lowering water-level in these valleys during the discharge.

Wallula Gateway high-level scabland.—A short, narrow canyon south of junction of Snake and Columbia rivers, 20 miles from nearest plateau scabland. Yet with same features of subparallel lateral canyons, rock basins, knobs, and buttes as high on canyon walls as in the Snake and Columbia upstream. All scabland drainage passed through this canyon, and the flood reached 900 feet above present river bottom, perhaps 650 feet above canyon bottom at beginning of Spokane episode. Constriction here caused the ponding recorded in lower scabland tracts on plateau and made possible the plexus crossings of divides. Erosion of Gateway Canyon was rapid enough to lower the ponded waters while the scabland rivers were still running. No other conceivable cause of ponding is indicated elsewhere in the Columbia Valley below the plateau.

Columbia Valley below Wallula Gateway.—For 150 miles a descending series of scabland tracts and gravel deposits in Columbia Valley.

A. *Bars in mouths of tributaries.*—Basalt gravel, ranging in height up to 600 feet above the Columbia. Delta foresets which prevailingly dip back into tributary mouths.

B. *Portland delta,* area 200 square miles, foreset bedded throughout, basalt gravel, channels, and great bars, remarkable eddy depression on upstream side of a rock island in the delta.

There are many apparently possible alternative explanations for the remarkable features of the preceding list. Virtually every one of these, when applied, involves exceptional combinations of factors, and no one of them will explain more than one or two of the fifteen listed phenomena. Most of them have been tested in the field and rejected. These extraordinary features must be treated as a *genetic system.* Their assemblage on, and limitation to, this little corner of the globe cannot be coincidence, as required by alternative hypotheses. The only genetic interpretation yet proposed which is inherently harmonious and which fits all known facts is that of a great flood of water abruptly issuing from the Spokane ice sheet. The unfilled rock basins with gravel bars perched on their walls indicate abrupt cessation of this flood.

The cause of this Spokane flood is unknown. It may have been a *Jökullaup* or glacier flood produced by subglacial vulcanism, but this hypothesis must stand or fall on field data not yet secured.

Virtually all of the alternatives proposed for the scabland phenomena spring from a belief that the flood hypothesis is essentially impossible, and a product of too hasty observation and immature reflection. Every alternative implies that field evidence and criteria exist which have not yet been found and which, if recognized, would notably alter the character of the writer's explanation, or would eliminate it altogether. Only three of the alternatives are based on personal study of any part of the scablands, only five on personal knowledge of the region in general. A belief that the flood hypothesis is an outrage obviously has been the stimulus for most of these alternatives. Yet the alternative hypotheses are valuable; indeed, necessary. No notable departure from proved types of interpretation should be accepted until it has passed the test of vigorous adverse criticism of others. No one observer can be trusted to apply the alternatives with sufficient rigor, especially so if he be the author of the "outrageous hypothesis." In the following pages suggested errors in observation are taken up first and a discussion of alternative generalizations follows.

MARGINAL SCARPS IN WEAK MATERIALS ABOVE THE BASALT

A persistent feature of the margins of scabland spillways is the 30°–35° slope in weaker material overlying the basalt. These are distinctly steeper and definitely younger than other slopes in the overlying sediments. If they are banks or bluffs of the glacial streams, as the writer's hypothesis holds, they record the following extraordinary conditions:

1. *Depth of the streams.*—The bases of some of the scarps stand 400 feet above the floor of closely adjacent preglacial valleys that carried glacial rivers.

2. *Width of the streams.*—There are fairly plane, fairly level scabland tracts as much as 20 miles wide between some of the scarps, yet their bases are essentially at the same altitude.

3. *Surface gradient of these streams.*—Altitude of bases descends 15 feet per mile for 75 miles along one wide route, 29 feet per mile along 33 miles of one narrow canyoned route, and there are comparable descents along most other routes.

4. *Contemporaneous occupation of the spillways.*—One large route has ten divergences from it, from 3 to 50 miles from the ice front, the bases of these scarps at each divergence being successively lower and comparable to the altitude of scarp bases margining the main spillway at the place of departure.[1]

Only one alternative hypothesis has yet been proposed to the writer for these scarps. Dr. G. O. Smith[2] reports similar features in Yakima Valley west of the scabland where the relatively weak Ellensburg formation above the Columbia basalt has been eroded back from the brink of basalt cliffs by wind and rain-wash, to produce a scarp overlooking bare rock above the cliff. This is the relation in many places in the scablands and gives plausibility to the suggestion.

[1] These conclusions may be denied by one unfamiliar with the field evidence and doubtful of the writer's ability to recognize the features he names. There is no remedy for such an attitude except a personal examination of the phenomena by the skeptic. This paper is written with the conviction that the items reported are facts. Details regarding altitudes of scarp bases and depths of preglacial valleys in basalt are shown on a map of the scabland to be published in the *Geographical Review* for July, 1928.

[2] Oral communication.

But there are many features of the scarps margining scabland that are not found in the Yakima Valley type of scarps.

1. Most of the scabland marginal scarps face flats which do not have cliffs descending to a canyon or deep valley a short distance in front of them. Yet they are of the same character and same degree of development as those with cliffs below them.

2. The exposure to wind and rain of the weaker overlying material, chiefly loess, is no greater in general along scabland margins than in the wide tracts completely covered with loess, yet such scarps are not found back in these tracts.

3. Basalt at the base of the scabland marginal scarps is channeled parallel to them and contains rock basins. The Yakima Valley scarps do not have these features.

4. Deposits of stream gravel lie on this channeled basalt close to the scarp bases. The gravel is clearly of the same date as the channeling and scarping; it was not uncovered by removal of loess. The Yakima Valley scarps do not have this.

5. The basalt of the channels and the basin walls, and constituting the stream gravel, is but little altered. The basalt exposed in front of the Yakima Valley scarps is mantled with fine residual waste except on the very brink of the cliff and in gullies that notch the edge of the cliff.

6. The scarps in Yakima Valley are almost everywhere furrowed by rain-wash. The scabland scarps have almost no furrows.

7. The slopes of the Yakima Valley scarps are gently concave. Those of the scabland are plane except at the very base.

8. The maximum width of the exposed basalt in front of the valley scarps is but a few hundred feet. In front of the scabland scarps it may be miles to the first descending cliff in basalt.

9. There are many minor spillways across loess-covered tracts, half a mile or less in width, yet bounded by scarps as steep and as high as those facing wide, flat scabland or overlooking deep scabland canyons. Parallel and immediately adjacent are valleys in the loess without scarps, without basalt ledges on the floor, without stream gravel; clearly unentered by glacial water.

10. Marginal scarps in weaker material above basalt, identical

in every respect with those in loess, exist in gravel and in piedmont cobbly waste. No wind or rain-wash could have made them.

11. Where the scabland and associated gravel deposits do not reach to the upper limit of basalt in preglacial valleys, there are no scarps or only weakly developed scarps of the Yakima Valley type.

12. Some minor spillways lead *out* of major scabland tracts through notches in the loessial scarps. The floors of these notches, bounded by their own scarps, may be 40 feet above the base of the scarps facing the larger tract.

It follows, therefore, that the alternative proposed cannot explain the marginal scarps in scabland. The features are similar only in a very general way, and in their origins are quite dissimilar.

HANGING VALLEYS IN WEAK MATERIALS ABOVE THE BASALT

In one place in the scablands there are several channels cut by glacial waters in a silt deposit (the Ringold formation). These channels mouth in the wall of Columbia Valley from 150 to 400 feet above the river. The entire wall is of the weak Ringold sediment. Basalt here is below river-level. The Ringold never could have maintained the lip of a cataract at the mouths of the valleys. The writer's interpretation has been that the surface of the glacial Columbia was as high along this wall as these channels now hang. Little or no deepening of Columbia Valley in post-glacial time and little retreat of the wall by undercutting have been allowed for in this explanation. A river at least 400 feet deep is therefore demanded for the highest channel mouth.

Mr. E. T. McKnight has offered an alternative explanation[1] to the effect that these channels have been left hanging by undercutting of the bluffs of Ringold silt, the Columbia Valley being deepened and the mouths of the channels becoming higher because shifted farther up their gradient. By this conception there was no hanging condition when the channels functioned.

In reply to this paper[2] the writer cited several features of the region which cannot be harmonized with McKnight's conception. A new item that has an important bearing on the alternative has

[1] "The Spokane Flood: A Discussion," *Jour. Geol.*, Vol. XXXV (1927), pp. 453–60.

[2] "The Spokane Flood: A Reply," *ibid.*, pp. 461–68.

come to light subsequently. It lies at the mouth of one of the hanging channels. By McKnight's conception, the original mouthing was at least 2 or 3 miles farther west, and lateral planation and deepening by the Columbia have destroyed this junction and removed all trace of deposits which the channel stream might have made at that place. Yet a newly graded roadway down from the hanging mouth of this channel to the Columbia has exposed 115 feet of sand and gravel, the top of which is the channel floor and the bottom of which is 125 feet above present high water in the Columbia. The material is composed of Columbia basalt and Ringold silt. The silt, as well as the basalt, occurs in pebbles, cobbles, and boulders. Some parts of the deposit are 50–90 per cent Ringold fragments. In other parts the weak Ringold fragments occur only as lenses in dominantly basalt débris. Foreset beds are common throughout, dipping out of the channel toward the Columbia. No long delta foresets were seen however. The current of the swollen Columbia into which this was deposited appears to have prevented their formation. There is no possibility of considering this material a part of the Ringold formation. If it is not a deltaic deposit lying on the slope of the preglacial Columbia Valley (perhaps in part filling a minor preglacial gully at this place), it must record 115 feet of filling in the channel 2 or 3 miles back from the mouth. This is obviously impossible, for the bottom of the deposit is as low as the junction of the channel and Columbia by McKnight's interpretation. His scheme cannot provide conditions for such aggradation. Indeed, he showed that channel deepening did not reach an equilibrium profile before the episode was closed. The deposit was made when the highest scabland channels were functioning, for its basalt was swept down from one of the remarkable divide crossings of the system. It constitutes a complete denial of the alternative offered by Mr. McKnight.

EROSION IN BASALT

The amount of erosion performed by glacial rivers across the plateau has been spectacularly great. No critic denies this. But the erosion of several canyons 300–900 feet deep across preglacial divides appears to demand a long time for each, and some sequence in development. Thus G. R. Mansfield says, "I am not convinced that so

much work could be done on basalt (by undermining and plucking) in so short a time, even by such a flood as is postulated."[1] Did plucking occur? Did it require a large volume? If these two points can be established, and if simultaneous occupation can be shown from other evidence, we perforce find ourselves staring catastrophism in the face.

The discontinuous deposits of coarse débris in the scabland have been called "gravel bars" by the writer, but some of these débris accumulations are so bouldery and so little assorted that J. T. Pardee[2] has called them "till" and "glacial drift." Their restriction to narrow linear scabland tracts, the multitudes of loessial islands all over the scabland with no trace of glacial overriding, and the large bordering loess-covered tracts, also "drift" free, indicate error in this interpretation. Glacial ice was involved, for there are a few granite boulders in these accumulations, but it was berg-ice floating in the scabland rivers. Mr. Pardee has never reiterated this interpretation during the development, or the criticism, of the flood hypothesis, and among his group, the men of the United States Geological Survey, no voice is raised against the conception of stream origin for channeled scabland. The bouldery accumulations may, therefore, be considered as bars. Indeed, all gradations exist between these boulder bars and the gravel bars.

The boulder bars lie in the lee of prominent ledges of large-columned basalt. No canyon walls are necessary; the ledges may be at the level of the deposit and in some places are actually lower. Some of the boulders are more than 6 feet in length, some still preserve traces of columnar outline, some lie on remnants of the sedimentary cover of the basalt, in one place[3] 100 feet above scabland ledges in the same slope and 2 miles from any ledges at their level. Here the preglacial valley floor was 250 feet below the lodging place of the boulders. These boulders were not carried by berg-ice. The associated gravelly débris on the sedimentary deposit indicates running water as the transporting agent. Plucking did occur. It was done in a stream at least 250 feet deep, a stream vigorous enough

[1] *Journal of the Washington Academy of Science*, Vol. XVII, No. 8, p. 206.

[2] "Glaciation in the Cordilleran Region," *Science* (Dec. 15, 1922).

[3] West-central part of sec. 4, T. 16 N., R. 28 E., a part of Drumheller Channels.

to roll huge boulders, where local conditions favored, up its channel sides or to keep them from rolling down as they traveled along its channel slope.

If the basalt floors left by the scabland rivers are preserved intact anywhere, it will be underneath the gravel bars. Evidence as to the character of the erosion of basalt might be expected in such contacts. One of them will be examined. It is shown in a gravel pit[1] 70 feet up on the slopes of a preglacial valley that carried a scabland river. Though not more than 15 miles from the edge of the ice, the gravel is 99 per cent basalt. Most of the fragments are very little worn, many of them with prominent re-entrant angles adding rude pyramidal points and thin sharp ribs to the outline. Similarity with fragments picked out of weather-fractured ledges of dense basalt is very striking. It strongly suggests that much of this angular gravel has been plucked out of ledges on the preglacial valley slopes, surely not worn off and probably not battered off. The angular fragments are largely of hard, nearly fresh material.

Below 10 feet of this gravel a wall of basalt has been uncovered. It has almost as hackly a surface as that of ledges never covered by gravel and crumbling ever since the episode closed. It has numerous re-entrant niches and pockets, some walls of which make an acute angle with the exposed face. Many are still filled with stratified fine gravel, as all were when the pit was first opened. The angularity of this exhumed channel wall is slightly smoothed; the sharp points and angles are gone. Perhaps a quarter of an inch of rock added to the angles would restore the original sharpness. This is all of the abrasion that is recorded. The wall wasted away far more rapidly by plucking than by abrasion. It can now be plucked by hand or by a little work with the geological pick. The ledge was not more than 30 feet below the upper surface of the glacial stream and had been fractured and loosened by centuries of pre-Spokane weathering. The glacial waters did their work here easily and rapidly though the depth was slight.

The fracturing involved is more intimate than the joints bounding and transecting columns. Weather-shattering begins along such joints but in many cases extends into the interior of the columns.

[1] In the northern part of the town of Wilbur.

Such rock along the Columbia, apparently unweathered, is described by army engineers as "hard to drill, but easy to blast." The sharp edges of the fragments indicate the notable lag of chemical decomposition behind physical disintegration. Indeed, in many road cuts and quarries on the plateau, the physical integrity of ledges appears to lie in the interlocking of already separated fragments. A little work with a pick, the removal of a key fragment, and a surprising amount of rock becomes loose and removable by hand.

The minimum depth for plucking must have varied with condition of the basalt and velocity of the water. Several places have been observed where a gradient of about 50 feet per mile and a depth of 30–50 feet was adequate to make rock basins and buttes with a relief of 15–20 feet.

A revision of the writer's idea of erosion in basalt by the glacial rivers has come from a recognition of the large preglacial capacity of most of the scabland coulees. The evidence for this appears elsewhere in this paper. The revised idea holds that erosion of basalt to make the scabland extended in most places but a few tens of feet below the rock surface which the rivers found when the loess had been swept away. The preglacial fracturing had made it ready for rapid removal. Broad scabland tracts and many scabland valley slopes, therefore, were simply vigorously scoured.

This conception, however, cannot be applied to canyons across preglacial divides or slip-off spurs, or to the higher cataracts. Here erosion in basalt occurred hundreds of feet below the original surface, but here again a factor not amplified in earlier discussion must be considered. It is difficult to present it convincingly as a general idea. The special conditions must be clearly visualized in order to understand the basis for the writer's argument. Only a brief statement will be presented.

Two crossings of one preglacial divide (between Palouse River and Snake River) occurred in the extreme southern portion of the scabland 65 and 80 miles by direct scabland routes from the southern limit of the ice sheet. Two canyons were thus produced; Palouse Canyon and Devils Canyon, each about 500 feet deep and each trenching the divide essentially to its base (Fig. 1). Palouse Canyon now carries Palouse River by a short-cut to the Snake. The aban-

doned portion of the preglacial Palouse (Washtucna-Esquatzel Coulee) is about 40 miles long, a mile wide, and much of it is 350 feet or so deep in basalt.

The evidence for this interpretation is as follows:

1. Tributary valleys of the preglacial mature drainage pattern, flowing from loess-covered tracts, enter Palouse Valley above the canyon, Washtucna-Esquatzel Coulee below the canyon, and Snake River Valley essentially with accordant grades.

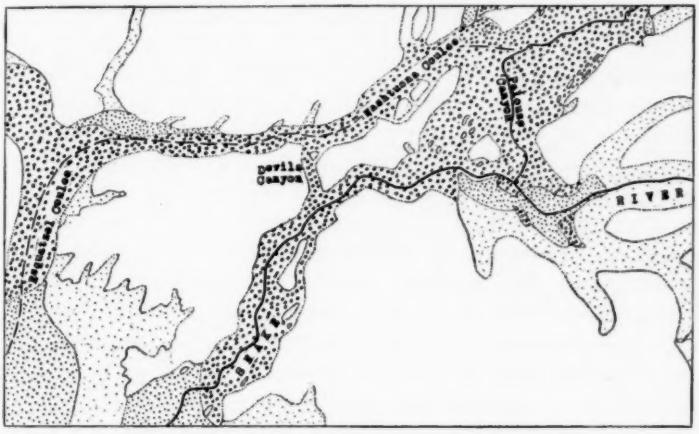

FIG. 1.—Sketch map showing old and new courses of Palouse River and associated features. Heaviest stippling indicates scabland; intermediate represents gravel deposits; and lightest shows areas with silt and sand. Blank areas are loess covered. Preglacial course of Palouse River shown by dashed line.

2. Palouse Canyon and Devils Canyon are exceedingly youthful features, very narrow, and bounded by cliffs that cannot be climbed in most places. Neither has tributary canyons. The length of both is limited to the width of the divide.

3. The descending surface gradient of glacial waters from the ice, recorded by loess scarp bases for 65 miles northward, crosses the old Palouse Valley 400 feet above its floor and continues without change as the base of loessial scarps bounding both canyoned spillways across the divide.

4. The great spread of channeled scabland on the divide along Palouse Canyon, high above all valley and canyon floors, with scarped loessial islands and gravel deposits, is identical with such features farther north. This denuded divide top with its deep transecting trench ties the divide crossing into the glacial-flood episode. So does the immense amount of scabland gravel in Snake Valley south of the crossing. Individual bar deposits here are 200–325 feet thick, and bar summits on the walls of the canyon are 500 feet higher above the river than any gravel in Snake Valley for at least 50 miles upstream. Glacial water did cross the divide, and Palouse and Snake valleys were as deep then as now.

When Washtucna-Esquatzel Valley and Snake River Valley are examined downstream from the divide crossings, the associated features of scabland basalt, of gravel deposits in separate great moundings, and of loessial scarps and even islands are found, identical with those north of the divide transections. The same descending gradients in the same profile are recorded. Only where contact of loess and basalt was higher than the surface of the great streams are the scarps absent. Furthermore, there is ample record of extensive ponds below the profile of the scarp bases in non-scabland valleys which enter the Snake and old Palouse. The upper limits of the silt, sand, and ice-rafted erratics deposited in these ponds are essentially the same as the profiles of the scarp bases across the mouths of the ponded valleys. That is, they vary from pond to pond, becoming lower with increasing distance down the Snake and old Palouse. The volume of glacial river waters in these two main valleys caused this ponding as it caused the overflow from the old Palouse.

With the special conditions of this district in mind, we may turn to the problem of erosion in basalt. How were the two canyons across the divide eroded? Earlier interpretations by the writer considered both the Palouse Canyon and Devils Canyon spillways to have cascaded notably in reaching the Snake. But profiles of scarp bases down both major preglacial valleys below these transections, and indeed down the Columbia for many miles beyond the plateau scabland, record the valleys as brimful and running over with the same flood. The scabland and great gravel deposits on the south side of the Snake at the Palouse Canyon spillway shows the same

thing. So does the ponding back up the Snake. There was no notable cascading down the south slope of this divide.

Yet the canyons are there, indubitably a part of the scabland system, a part of the record all over the face of the plateau that preglacial valleys were not adequate to the task imposed on them and that they became channels for the glacial rivers. Where the subfluvial slopes descended steeply in the direction of the current, plucking in the basalt reached much below the zone of preglacial weather fracturing. Such slopes, doubtless in part as short, high-gradient, preglacial tributaries, were available on the south side of the Snake-Palouse divide. Indeed, the lower part of both Palouse and Devils canyons indicates modification of such tributaries. The mechanics of subfluvial cascades must differ from those in which the stream surface descends notably over the ledges. The deep rock basins of scabland indicate the same mechanism. Few of them were eroded at the foot of cascades or cataracts. Most of them are products of current flow across, not current plunge into, them.[1]

It is difficult to conceive of the conditions which made glacial river bottom of such tracts as long continued. It is impossible by any suggested hypothesis that the Snake-Palouse divide crossings were long continued. If one insists that the conception of rapid plucking is impossible, the field facts and relations here presented must be dismissed, and refuge can be taken only in the assertion that "not enough is known in detail of the glacial geology and physiography of the region to furnish an adequate basis for any connected story of events here."

BARS

The writer's descriptions of the great glacial river canyons of the plateau have conveyed the impression that they are "very striking," "astounding," "bizarre," etc. But they are canyons nevertheless. A small stream may make a large canyon. No large canyon was ever known to be filled to the brim with its own stream. That they could be canyons developed below river-level was very difficult to

[1] Such must have been the origin of the Rock Lake Basin (more than 7 miles long and reported to be 250 feet deep), of the large basins in Othello Channels, one of them 2¼ miles long and more than 100 feet deep, and of the 182 rock basins in Drumheller Channels, one of them a mile long and more than 100 feet deep.

believe. Failure to appreciate such features as preglacial depths, height of present scarp bases above the preglacial floors, the great rock basins in them, the great improbability of divergences far from the edge of the ice without great volume, nullifies such critic's judgment of the argument for river-channel origin.

It is significant, however, that in the chorus of disapproval[1] no one attacked the interpretation of the mounded gravel deposits as bars. Though small streams may erode large canyons, obviously they cannot build bars any thicker than they are deep. Dr. Mansfield comments on high-level and low-level gravel bars, but fails to remark on bars one-half to three-fourths as thick as the canyons are deep, though these had been described. When the writer subsequently[2] took special care to emphasize the magnitude of the bars and in unescapable consequence the enormity of the rivers which built them a simple disposition was at hand. Such deposits cannot be bars! So one critic suggests that they are deltas or remnants of deltas, the foresets of the growing faces of the bars only delta foresets. Gravel deltas are conventional affairs; thick deltas are common enough. The whole difficulty vanishes at the magic of a word—except the difficulty of explaining their situations, their distribution their parallelism of structure with form, their lack of erosional shapes, and their composition. Detailed explanations of each of these "bars" with foreset bedding as deltas may give geology a wilder hypothesis than the "Spokane flood."

Mr. McKnight accepts the writer's published interpretation of the 200-foot relief features in river gravel near Hanford, Washington, as bars and channels, though he says, "I still believe that they are no larger than can be ascribed to the glacial Columbia as it has ordinarily been conceived heretofore."[3] Later examination of the Hanford region has shown that stream gravel, indistinguishable from that in the 200-foot bars, extends westward up on a definite terrace 200 feet still higher. This terrace may be underlaid largely by Ringold silt, but it is almost completely mantled with the gravel.

[1] Discussion in the *Journal of the Washington Academy of Science*, Vol. XVII, No. 8 (1927), pp. 203–8.

[2] At the Cleveland meeting of the Geological Society of America (1927).

[3] Personal communication.

These deposits with 400-feet vertical range lie on the west side of the Columbia in the concavity of a great eastward curve of the river.

Another gravel deposit in the district has also been studied. It lies on the east side of the river inside the first large reverse curve upstream. It is a huge rounded mound of basaltic débris, grading from cobbles and pebbles at the base (about 550 feet A.T., 75 feet above the river which is 2 miles away) into coarse basaltic sand at 825 to 850 about 5 miles farther back from the river. Still farther eastward its surface descends to lower land. There is no terracing on the broad convex slopes. The material everywhere appears fresh at a depth of about 2 feet. It belongs to the same class of mounded gravel deposits as those west of the river near Hanford. If it is not a glacial river bar, then the other features are not bars. When the gravelly débris was swept back and sorted out in this great pile, the river was as deep as the pile is high, 300 feet.[1] If the present Columbia course among these bars was inherited from the glacial stream[2] and has not been deepened subsequently, that river at the south end of the bar was 450 feet deep. These features record a river assuredly greater than the glacial Columbia has ordinarily been conceived heretofore.

DIVIDE CROSSINGS

Hundreds of minor divides of the preglacial dendritic drainage pattern in loess were crossed by the glacial waters. In most of these the erosion exposed basalt continuously through the notched divide and down the entered valley. Also, by widening the valley, it produced marginal scarps in the loess. In some places where two parallel adjacent valleys were entered, the divide was reduced to a row of relict hills surrounded by scabland and gravel deposits. These features are characteristic of the upper limit records of the flood. In most places they constitute the whole record.

But there are at least eight other places on the plateau where the basalt also was deeply eroded. Two of these, Palouse Canyon and Devils Canyon, have been noted. Four others will be briefly

[1] Though there may be Ringold underneath in part.

[2] Evidence for this presented in "The Spokane Flood; A Reply," *Jour. Geol.*, Vol. XXXV (1927), pp. 461–68.

described and alternatives to the flood hypothesis tried on them. These four are all associated with discharge from Quincy Basin.

Quincy Basin (Fig. 2) is a broad, shallow, downwarped tract in the western part of the scabland, containing about twenty-five townships of land. A pronounced monocline, Badger Hills, rises northward from it, and a definite anticline, Frenchman Hills, bounds

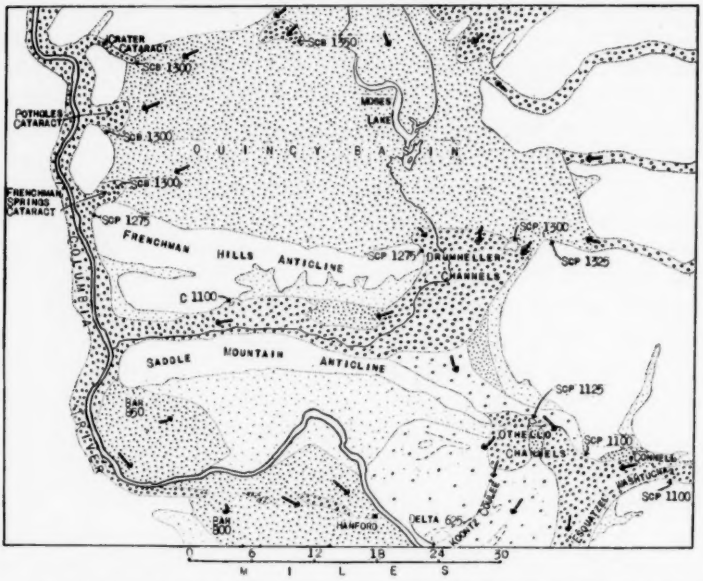

FIG. 2.—Sketch map showing discharge ways from Quincy Basin. Heaviest stippling indicates scabland; intermediate indicates gravel deposits; and lightest represents ponded areas without much current. Channeled tracts without much scabland are shown by widely spaced heavy stipple marks. Abbreviations with altitude figures as follows: *Scp*=scarp base; *C*=channel floor; *Scb*=highest scabland. Heavy arrows indicate direction of flow.

it on the south. Its western edge, close to the brink of Columbia Valley but about 800 feet higher, is determined by a gentle westward rise in the slightly warped basalt flows. Less definite upwarpings lie east of the basin. All of these structures are topographic features. This basin received all glacial drainage from the north for more than 60 miles along the ice front and also received all but one

of the large divergent rivers from the great eastern scabland tract. Into this basin was carried an enormous amount of basalt gravel and sand. Only two occurrences of scabland are known in it. All else is deeply buried by this débris.[1]

Four discharge ways from the basin have operated at some time or other during the deposition of the great gravel fill, three crossing the western rim and descending over the bluff of Columbia Valley. They are Crater Cataract, Potholes Cataract, and Frenchman Springs Cataract. One, following the preglacial discharge route, opens out from the southeast corner of Quincy Basin, crossing the tip of Frenchman Hills anticline in Drumheller Channels and leading thence westward to the Columbia. The westward course is along a synclinal valley, between this anticline and a higher one (Saddle Mountain) parallel with it and 6–10 miles farther south.

Of these four discharge ways the three breaches in the western rim are divide crossings. Probably short, steep, preglacial tributary canyons to the Columbia existed here, but they carried only the drainage of the western rim itself. The bottom of the very much larger southeastern route, Drumheller Channels, is today 300–400 feet deeper in basalt than the channels leading to the three western cataracts. Stream-formed scabland in Drumheller Channels, below the altitude of the cataract heads, is fully 9 miles wide. Only a small part of this great channel width can be termed preglacial. It is almost wholly a product of glacial water. This must be granted by such critics as Dr. Mansfield who, to avoid the inference of great volume in spillways both wide and deep, remarks as follows:

> It does not seem to me necessary to assume that all the scabland channels, or even that all parts of the same channels, were occupied by water at the same time. Mr. Bretz notes that deep and shallow canyons unite and divide in labyrinthine fashion. Perhaps some of the shallower channels were formed earlier than some of the others and now hang on the sides of more favorably located channels.

If his suggestion be correct, then preglacial drainage here had made no valley or canyon across the nose of the anticline. This is saying either (1) that Quincy Basin had remained an undrained basin or

[1] There are lake sediments under much of the débris. The Quincy Basin gravel does not, therefore, follow the prevailing rule of lying on scabland surfaces of basalt.

flat while most of the plateau had developed a mature topography, or (2) that the basin-making was later than the mature topography of the plateau.

Despite its improbability, let us grant this view. The basin then had no adequate discharge way when glacial water arrived, but during glacial discharge four spillways were formed. They operated either simultaneously or in some sequence. The combined width is $12\frac{3}{4}$ miles. This is too great, let us say, to permit the idea of simultaneous functioning. If in a sequence one may hold that the "more favorably located" Drumheller channels eventually obtained all the discharge. But this requires initial contemporaneity with that unheard-of width of $12\frac{3}{4}$ miles. However, we may have a sequence with Dr. Meinzer who argues[1] that "tilting and folding of rocks have in this region occurred in recent geological time, probably during and since the cutting of the Pleistocene channels." Such a tilting applied here would require operation of only the three western spillways at first (again no preglacial drainage out of the basin allowed), then later by raising the western rim or by depressing the nose of Frenchman Hills anticline, or both, the discharge would be shifted to the southeast, the cataracts thus becoming abandoned. What is the field evidence for or against a shift of this kind?

The evidence lies in the upper limit records at each of the discharge ways and in the depths of the three notches across the western rim. Above the upper limits of glacial water is a loessial mantle with smooth slopes overlying Ellensburg (?) and basalt; below is scabland and associated gravel. At the contact there may be a scarp in the loess or other weak material on the basalt. Unless the weak material was thick enough and the current at its base was vigorous enough, no scarp may be expected. And even if a scarp exists, one cannot be sure that its base was the water's surface. The water may have been somewhat higher, though the error involved cannot exceed the height of the scarp.

A careful field study, aided by the excellent topographic maps of these spillways, has shown that the upper limits do not range more than 25 feet above or below 1,300 feet A.T. though they are

[1] Discussion in proceedings of the Geological Society, *Journal of the Washington Academy of Science*, Vol. XVII, No. 8.

35 miles apart east and west and distributed through 18 miles of distance north and south. The short channels leading to the two southern cataracts are almost 100 feet below these upper limits, i.e., 1,200 feet A.T. No shift to Drumheller Channels would occur until that tract had been tilted down to about 1,200. The record of initial spill there, however, is actually as high as at the cataracts. There is only one possibility of retaining the conception of shift by tilting; it is that reverse tilting later has raised the Drumheller upper limits just high enough to coincide with the cataract upper limits. This alternative has not yet been urged.

Another fact to consider while dealing with Quincy Basin discharge is that the combined width of the three cataract channels is $3\frac{3}{4}$ miles while Drumheller is 9 miles wide. By the alternative we are considering, it should not be half of that.[1] The reader will keep in mind that this argument of sequence by tilting is built on the assumption that there was no preglacial drainage route through the Drumheller tract and that this assumption is of doubtful value.

[1] Dr. Meinzer comments that "Quincy Valley (or Basin) into which the waters of Grand Coulee discharged evidently became the scene of a lake in which sediments were deposited and which at first discharged westward into the valley of Columbia River, forming several cataracts that retreated some distance in normal fashion before they were abandoned." *In Water Supply Paper 425*, Schwenneson and Meinzer have described a part of these lake sediments as clays containing volcanic ash, shells, bones, petrified wood, and certain dark layers charged with organic material. How do these characteristics agree with the conception of Grand Coulee River in which a waterfall 400 feet high and $2\frac{1}{2}$ miles wide existed, the retreat of which fall made the lower part of the coulee? Was most of this basalt ground to clay before it reached the lake? Was the shallow lake undisturbed by an inflow certainly greater than the present Columbia (plus the great glacial streams from the northeast and east, not considered by Dr. Meinzer) and by an outflow which maintained the three cataract rivers $\frac{1}{4}$, $1\frac{1}{2}$, and 2 miles wide? Would such a lake maintain three cataracts simultaneously while recession as great as 2 miles occurred? Would it maintain two of these cataracts while 100 feet of channel deepening in basalt above the falls occurred for almost the full width of $1\frac{1}{2}$ and 2 miles? Would it possess these organic remains? It seems far more probable that the lake took origin as soon as the basin began to be formed. It is much more probable that Grand Coulee River is recorded in the coarse and very little-weathered gravel which is as much as 90 feet (Schwenneson and Meinzer's figures) thick above the lake sediments. Indeed, older and considerably weathered stream gravels are known in a few places beneath the scabland gravel of the basin. Do they not record a long interval between the time of the lake and that of Grand Coulee and the four great discharge ways? Do they not record establishment of drainage across an obliterated lake before the scabland-making episode?

However, the whole history of glacial discharge from Quincy Basin has not yet been told. What is perhaps its most striking feature now will be considered. It is a small edition of Drumheller Channels lying on the eastern nose of Saddle Mountain anticline. The discharge here also was southward across a labyrinth of rugged buttes and deep basins carved from the tilted basalt flows. The character of the group (Othello Channels) is well shown in Figure 3. Like Drumheller Channels, also, it has a relict island of weak sedimentary material standing among the channels on the axis of the uplift. In two features, however, it differs. There clearly was no preglacial drainage across the anticline here, and the channel floors (not considering rock basins in them) are from 100 to 300 feet higher than the tract just to the north, whence came the water.

Othello Channels is a divergence from the great spill out of the southeast corner of Quincy Basin, taking origin several miles south of the main Drumheller plexus. At its head it is a hanging valley to the main synclinal valley but with reverse gradient. This reverse hanging valley leads southeastward for 8 miles before the labyrinth or plexus is reached. The plexus group is about 6 miles wide on the axis of the gutted fold and about 3 miles long with the canyon-channel lengths. The largest channel, the easternmost, is shallowest. The floor of the canyon containing Scooteney Lake is more than 200 feet below that of this eastern channel. So with the canyon west of Scooteney.

Let us try Dr. Mansfield's idea of sequence here.[1] The floor of the wide channel is below 950 A.T. at the col. Abandon this in favor of the two narrow canyons west of it whose floors are below 725, but whose combined width is hardly half that of the easternmost channel and whose walls reach to 950 and 1,000 feet A.T. This seems a bit difficult. But if unwarily insisted on in order to avoid occupation of all channels throughout the whole episode, the disconcerting fact comes to light that the deepest parts of these canyons

[1] Dr. Meinzer will be interested in this also for he says: "Unless there is conclusive proof, it should not be assumed that along any drainage line the erosion work at high and low levels was done simultaneously. It would seem more probable that the work of erosion proceeded during a long time and that the high level channels were abandoned as the stream cut down to lower levels."

FIG. 3.—Othello Channels. Part of Scooteney Lake, Washington, topographic map, U.S. Geol. Survey

are closed depressions more than 100 feet deep.[1] Water to flow through them had to cross floors 850 and 875 feet A.T. about a mile farther south (see Fig. 4, sect. *D–D'*). And only a very narrow stream could get out at these altitudes. To get a width comparable with the rock-basined parts of the canyons, the waters had to rise at least to 900 feet A.T. To get an erosive ability adequate for the basin-making (see Fig. 5), a stream depth equal to basin depth can

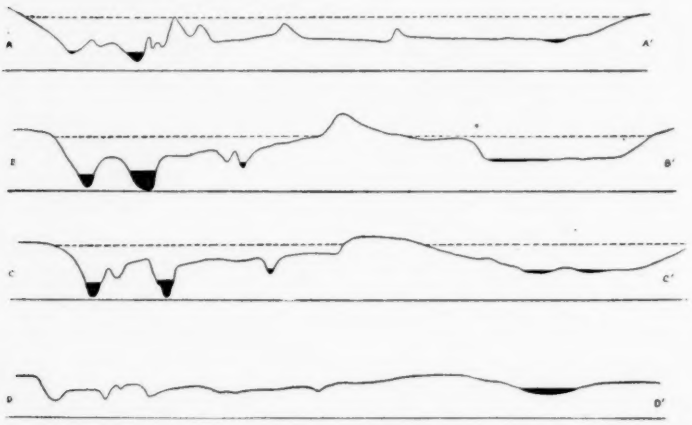

FIG. 4.—Cross-sections of Othello Channels. Base line in each is 700 ft. A.T. Dashed line, indicating upper limit of glacial water, is 1,125 ft. A.T. Basined portions of the channels are black.

hardly be denied. Since about half the canyon depth is rock basin, such a stream surface would be up to the top of the canyon walls, higher than the floor of the channel which we are endeavoring to abandon. Since a stream fully as wide as these two canyons together would have continued to flow through the broad eastern channel if the glacial river surface had been but a trifle over 950 feet A.T., it is obvious that the alternative idea of succession in use never was constructed from a careful study of the Scooteney Lake topographic

[1] The 825 contour in the western canyon, shown on the Scooteney Lake topographic map of the U.S. Geological Survey, should be hachured. It is a closed contour.

map. All parts of the Othello Channels plexus must have functioned simultaneously during their whole history.[1]

But how did these western canyons in basalt originate? The eastern channel has been eroded but little in basalt, has no conspicuous basaltic knobs on its floor, and has the relatively weak Ringold or Ellensburg for most of its eastern wall. With an "orderly and long-continued" episode of stream erosion across this divide all the water would have gone around the anticlinal nose, as the eastern broad channel essentially does. The answer is found in the upper limits record at Othello Channels. This is clearly preserved on the relict hill of sedimentary material in the plexus. Scabland extends up to about 1,100 on the sides exposed to the current (north and west sides). The scarp base is 1,125. This would put water over all the scabland buttes separating the canyons. It would provide the only means of *initiating* these canyons. If this level were maintained or approximately maintained to the close of the episode, it would have required water 400 feet deep over the rock basins in these canyons. Whether or not that depth was required for their production, something more than streams 30–40 feet deep obviously is demanded. Yet this is all that can be allowed by Dr. Mansfield's hypothesis of succession.

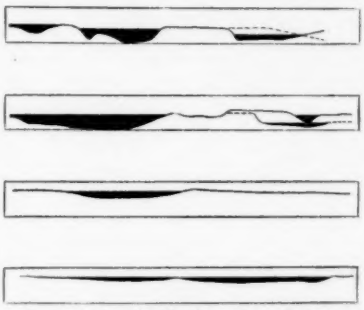

FIG. 5.—Longitudinal profiles of the bottom of four of the Othello Channels. Base line in each box is 700 ft. A.T.; top line is 1,000 ft. A.T. Westernmost channel is at the top; the broad eastern channel, at the bottom. Basined portions in black. Downstream bifurcation of two channels is shown.

The remaining question concerning Othello Channels may now be considered. It is the extraordinary height reached by the glacial

[1] Perhaps it will aid in visualizing the aberrancies of these labyrinths to consider the eastern divergence of the western rock basin. It lies in the northeast corner of sec. 14 and the west central half of sec. 13. It is more than 75 feet deep yet it *ends* at the south, its floor rising 100 feet in less than 1,000 feet of horizontal distance. The water which made it flowed south.

streams across this divide. The upper limit is scarcely 200 feet lower than at the head of Drumheller Channels, 22 miles distant by drainage routes. Water certainly had to go through the Drumheller tract before it could use the Othello route. This 200-foot descent was not bottom gradient for Othello Channels was above preglacial drainage routes. Did the enormous streams called for by the Spokane-flood hypothesis have *surface* gradients of 10 feet to the mile? The answer for this particular case should be found along the main synclinal route westward from Drumheller to the Columbia. If this syncline was not a preglacial drainage line, its floor at the inception of the flood might have been essentially as high as the eastern plunging end of Saddle Mountains anticline. If it was a preglacial valley, it might have been blocked in some way to cause the southward discharge through Othello Channels, though an "orderly and long-continued" blocking would be difficult to defend.

Dr. J. P. Buwalda has suggested[1] that the profile of both Ellensburg and Ringold remnants in the region be considered. Perhaps such sediments filled the syncline at the beginning of the discharge, though basalt certainly did not. Large remnants of what will be considered Ellensburg do occur in the syncline today. Lower Crab Creek in the scabland channel hugs the south side of the asymmetrical downfold. Along the northern side of the syncline there is a dissected terrace of Ellensburg 3–5 miles wide and 500–700 feet above the creek. Much of it lies above 1,100 A.T. There are numerous short valleys eroded in it, draining the southern slope of the Frenchmen Hills upwarp (Fig. 6). They do not have the maturity of valleys in the loess-covered tracts farther east. This may be due to greater resistance to erosion of the sandy and calcareous Ellensburg material or to less rainfall in this western part of the plateau, or to both. But their capaciousness and the development of their tributaries requires a long preglacial history. The upper-limit scarps all over the plateau record very little post-glacial erosion in loess, a weaker material and generally under a heavier precipitation. With this evidence should be considered the strong probability that the preglacial Crab Creek drainage, more than 4,000 square miles in area, left Quincy Basin through the site of Drumheller Channels instead of over one of the three cataracts. A syncline so near the Columbia

[1] Oral communication.

FIG. 6.—Part of Red Rock, Washington, topographic map, U.S. Geol. Survey

and opening into it could not escape becoming a drainage route. The idea that the syncline was filled with Ellensburg when Drumheller Channels first operated is therefore dismissed.

But other suggestions are at hand, calling for a dam of some sort in the preglacial lower Crab Creek Valley, a dam which shall be high enough to produce the Othello Channels divergence and which shall endure long enough for 250 feet of erosion at the channels in basalt, "a hard rock and very resistant to corrasion." Glacial ice as a dam is barred. Trustworthy observers have long since shown that no glacial ice on the plateau got within 50 miles of this valley. River-borne ice may be permitted, however.[1] M. R. Campbell blocked the old Kanawha (Teay Valley) with it, making several dams 100–150 feet high where the valley was a mile or two wide. These lasted long enough for the trenching of new courses, necessitated by the dams, deeper than the old.

In lower Crab Creek the best place for an ice jam is near Beverly where there is a minimum width of 3 miles between the 1,100-foot contours. The scabland valley floor here is 500 feet A.T. This is not far below the upper surface of the basalt. The dam, therefore, was not much less than 600 feet high. If we endeavor to reduce the height of the dam by locating it farther up the valley, one as low as 500 feet can be had, if width of valley is not important. The lower dam would be 6 miles long. Adjust these items as one will, within the limits permitted by the field evidence, construction of a dam of river ice yet remains a formidable task. Then maintain such a dam here even for the shortest time required for the erosion of Othello Channels, being careful that the abundant floating ice does not block the shallow and interrupted new spillway also. Perhaps this is plausible to some. The procedure has good precedent. But it quickly passes into a purely fanciful idea when we consider (1) that hundreds of these high-level divergences are to be provided for over the whole scabland and for 200 miles farther down the Columbia and (2) that in every case, including lower Crab Creek, the record both above and below the divergence is not that of ponding but of vigorous flow identical with the divergence record itself. Most of these divergences could take care of but a small fraction of the main channel discharge, anyway.

[1] Personal communication from H. G. Ferguson.

However, let us examine the character of lower Crab Creek.

1. A very coarse basalt gravel deposit has been opened north of Corfu Station. In one short cut through the edge of a terrace a thousand or more boulders 3–4 feet in diameter have been rolled out along the roadside. This is 835 feet A.T., 260 feet above the creek which is 2½ miles to the south. The stream which deposited them was more than 3 miles wide and, by the argument for a preglacial valley here, was more than 200 feet deep.

2. Natural Corral (Fig. 6) is a typical scabland coulee north of Colletta Station. It is a hundred feet deep, nearly 3 miles long, and a quarter to a third of a mile wide. Its name suggests the character of its walls. It is "tributary" to Red Rock Coulee though at the junction it is ten times as wide. Scabland on the brink of its cliffs is 850–75 feet A.T. It lies parallel with the creek valley only a mile and a half distant. Its flat floor is a third as wide as that of the main valley and in its lowest place (a closed basin) only 100 feet higher. At its head is a cataract more than 50 feet high, and the map shows clearly that, east of the head, the eroding waters came out of Crab Creek Valley. It is a subfluvial canyon and cataract, a record of the great plucking which the glacial stream performed.

3. Five miles farther west is another very similar scabland feature except that it has no cataract head. It has no head at all. It is a canyon 4 miles long and 150 feet in minimum depth, nearly half a mile wide, a loop out of Crab Creek Valley and back into it. Both ends hang, the upper end more than 300 feet above the main valley floor. The scabland brink of its walls is 1,000 feet A.T.[1]

4. Cash's Butte, a relict hill of Ellensburg, lies between these two curious canyons and a little north. The glacial water had to rise above 1,100 here to initiate the channel which isolates the butte. This channel floor is 575 feet above the creek, 3 miles to the south. And lower Crab Creek Valley, 3 miles wide, leads thence to the Columbia only 11 miles farther west. These features of lower Crab Creek tell clearly why Othello Channels functioned. They debar any hypothetical ice jam or blockade of any kind.

Another alternative for the high altitude of Othello Channels on Saddle Mountain anticline is the obvious suggestion that the anti-

[1] The contact of Ellensburg and basalt is about 200 feet higher here than at Natural Corral.

cline has undergone renewed movement since the channels were eroded. When Mr. McKnight failed to discuss the divide crossing in his scheme for the hanging valleys near Hanford, the writer listed several possibilities that theoretically were compatible with his conception. Mr. McKnight's preference was for post-channel uplift along the Saddle Mountain anticline.[1] By this, of course, the great depth in the syncline might be avoided and his hypothesis might at least be consistent with itself. But would it be consistent with the field evidence? Othello Channels' upper limit, 12 miles south of the divergence, is only 25 feet higher than the synclinal river's upper limit at Cash's Butte, 18 miles west of the divergence. There is no way of knowing just how high the water was on the steepened slopes of the relict hill in Othello Channels or just how deep it was in the channel back of Cash's Butte, but the summit of the butte is less than 1,175 and the surface of the flood here was below the top of the butte, yet above 1,100. The base of the Othello Channels' relict hill scarp is 1,125, and the flood water must have been that high. This altitude is below the top of Cash's Butte and shows clearly that there has been no detectable differential movement in the region since the channels were abandoned.

Preglacial drainage through the valley of lower Crab Creek is almost as clearly recorded as through Washtucna-Esquatzel Coulee. A very great glacial river in each valley is also well recorded. The divergences in both are due to the same cause, a brimming over and an escape southward toward lower tracts. The flood hypothesis has been built strictly on field evidence. It fits every item of the record thus far found in these valleys. No other hypothesis does. Several have no field evidence to support them; others are untenable because certain features of the region obviously disprove them. The only objection yet raised to the flood hypothesis for divide crossings is its demand "for a seemingly impossible quantity of water."

TALUS RATIOS

The writer has stated that Spokane spillways have talus deposits against their cliffs, $\frac{3}{4}$ to $\frac{4}{5}$ the original height of the cliffs, while Wis-

[1] Personal communication. An adjustment between alternatives is needed here, for Meinzer would bring the nose of Frenchman Hills anticline down while McKnight would raise the nose of the parallel and nearby Saddle Mountain anticline. It is similar

consin spillways have $\frac{1}{2}$ talus, and that this ratio may be used for identification of channels of two different episodes. This idea has been vigorously attacked, both as to accuracy of the statement and as to its trustworthiness as a criterion of age. Buwalda[1] believes that height of cliff is an important variable factor; Pardee and Gilluly, that the direction the cliff faces should be a variable, at least in talus which has not reached an equilibrium profile; Gilluly, Buwalda, and Mansfield, that rate of talus growth "is so slow that considerable time intervals would fail to register significant differences;" and Gilluly, that the range in rainfall on the plateau should be recorded in talus height unless a relatively stable stage has been reached.

Some of these points are well taken. They are additions to the variables earlier pointed out by the writer; viz., ashy and scoriaceous phases of the basalt, ellipsoidal structures in certain flows, prominent platiness in the columns of some flows, variations in size of columns, steep tilting of flows in some tracts, removal of material by streams, filling of basins at foot of cliffs, and addition of windblown material. But the weakest point in the argument from talus ratios was not recognized either by critics or the writer. It is the assumption of vertical cliffs. The writer has seen enough sections in the talus accumulations since his idea was published to show that this assumption is unwarranted. The buried cliff faces vary considerably in slope. Also enough departures from the $\frac{3}{4}$ to $\frac{4}{5}$ ratio have been found in the same channel to show that this ratio is realized only in a general way.

Talus ratio still remains a criterion for separating Wisconsin channels from older ones. That the older ones can by its use be classed as of the same glacial epoch may be an open question. That *simultaneous* operation can be established by its use has never been argued by the writer. His use of the term "contemporaneous," as is shown by the context, has been simply to denote the same glacial epoch. The belief in simultaneous development is based on other evidence, to be presented in the next division of this paper.

[*To be continued*]

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to the adjustment needed between the ice jam in lower Crab Creek and the conception of long-continued erosion in making Othello Channels.

[1] Personal communication.

ALLUVIAL FANS OF THE CUCAMONGA DISTRICT, SOUTHERN CALIFORNIA

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ABSTRACT

Along the south margin of the San Gabriel (California) mountain block alluvial fans have accumulated to a thickness of a thousand feet and more. The whole series of sediments is a unit, still growing, but chiefly of Pleistocene or earlier age. The fans are being dissected, with the formation of fanhead trenches and midfan mesas. The trenching of the fanheads is chiefly a normal, somewhat late feature of the fan development, though recent uplift, indicated by well-preserved fault scarps, has been a factor, and climatic changes may have contributed to the result. The midfan mesas may be the indirect result of faulting now obscured.

INTRODUCTION

Large alluvial fans have been built up by the outwash of streams draining the southern slopes of the eastern part of the San Gabriel Mountains, in the Cucamonga and San Bernardino quandrangles, Southern California (Fig. 1). The coalescing fan surfaces form a gently inclined plain which slopes from the bold mountain front to the Santa Ana River, a distance of 15–20 miles. The upper slopes of the plain are cut by numerous stream trenches and interrupted by isolated or nearly isolated dissected fan remnants. This paper will deal especially with these topographic irregularities and will attempt to determine their significance as to underground structure and physiographic history.

ACKNOWLEDGMENTS

Professor W. M. Davis proposed the area as a field for investigation and made suggestions concerning the faulting and concerning the organization of this paper. The work was carried on under the encouragement of Professor A. O. Woodford, of Pomona College. Professor J. P. Buwalda, of the California Institute of Technology, criticized the manuscript. John C. May, student colleague, aided in the field. Well logs and rainfall records were kindly furnished by many persons.

PREVIOUS INVESTIGATION OF THE REGION

Previous geologic investigation in this area has been slight. The only paper of importance is W. C. Mendenhall's "The Ground Waters and Irrigation Enterprises in the Foothill Belt, Southern California,"[1] in which the alluvial deposits and surface features are briefly described.

CLIMATE

The climate of this region is mesothermal humid, chiefly of the hot summer Mediterranean type.[2] There is an abundant winter rainfall in the mountains, which rapidly diminishes with lower elevations, until aridity is approached at the outer margins of the alluvial fans. The available data indicate that the rainfall over the entire mountain drainage averages at least 35 inches annually, whereas the average over the alluvial fans is about 17 inches. Snow may cover the higher peaks (8,000–10,000 feet elevation) for several months during the winter. Talus slopes and bare rock surfaces are abundant near the summits, and the smaller ravines seem to be choked with débris. The abundance of talus may be due largely to the varied effects of cold climate. Despite rather sparse forests, the bare heights are in marked contrast to the brush-covered, rain-absorbing lower slopes of the mountains.

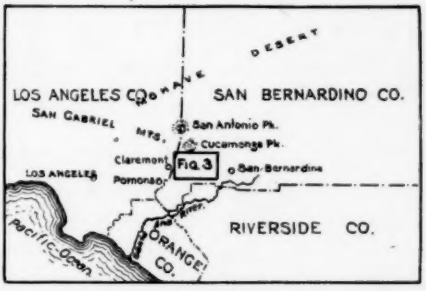

FIG. 1.—Sketch map of a portion of southern California, showing the location of Figure 3.

The run-off from storms is seldom sufficient to carry coarse débris out onto the fans more than once or twice during the winter, and in dry winters it often fails to do so at all. During occasional years when rainfall is excessive and concentrated into a short period,

[1] *U.S. Geol. Survey Water-Supply Paper 219* (1908).

[2] R. J. Russell, "Climates of California," *Univ. Calif. Publ. in Geog.*, Vol. II (1926), pp. 73–84.

much débris is carried entirely across the fans into the Santa Ana River.

STRUCTURAL DIVISIONS

The area described here includes a small portion of the San Gabriel Mountain block and a larger portion of the relatively low block to the south. The east-west Sierra Madre fault zone[1] separates the complex crystalline rocks of the San Gabriel range from the unconsolidated alluvial deposits upon the depressed block.

The alluvium seems to have a thickness of about 1,000–1,200 feet, with local diminutions due to prominences in the bed rock. Many wells up to 1,000 feet in depth have failed to reach the base of the alluvium. One well a mile and a half from the mountains entered bedrock at 1,000 feet, and three other wells farther from the mountains, and widely spaced, reached bed rock at depths of 800 to 1,200 feet.

THE MOUNTAIN FRONT

The eastern part of the San Gabriel Range has a steep, straight south margin. The mountain front is divided into an upper and a lower portion by indistinct benches at about half height. The benches south of the summit ridges vary in elevation from about 4,200 feet to 6,000 feet. They seem to belong to an erosion surface of moderate relief whose remnants form the rather even top of the range farther west.

The difference in elevation between the half-height surface and the bed-rock surface of the relatively depressed block suggests a differential vertical movement of 4,000–5,000 feet.

The frontal scarp of the range is cut through by four canyons, which extend 4–9 miles into the range. These major canyons, from west to east, are San Antonio, Cucamonga, Deer, and Day (Fig. 3). At the narrow east end of the range, Lytle Creek cuts through from the northern side of the mountains, where it has a drainage more extensive than that of any southern canyon mentioned.

The battered range-front facets below the half-height region have frontal slopes of 15°–30°. They form a scarp which runs almost due east from Cucamonga Canyon toward Lytle Creek, and gradually

[1] William S. W. Kew, "Geology and Oil Resources of a Part of Los Angeles and Ventura Counties, California," *U.S. Geol. Survey Bull. 753* (1924), p. 100.

FIG. 2*a*.—View northwest, from Santa Fe Railroad near Cucamonga. *SA*, mouth of San Antonio Canyon; *CC*, mouth of Cucamonga Canyon; *RH*, Red Hill.

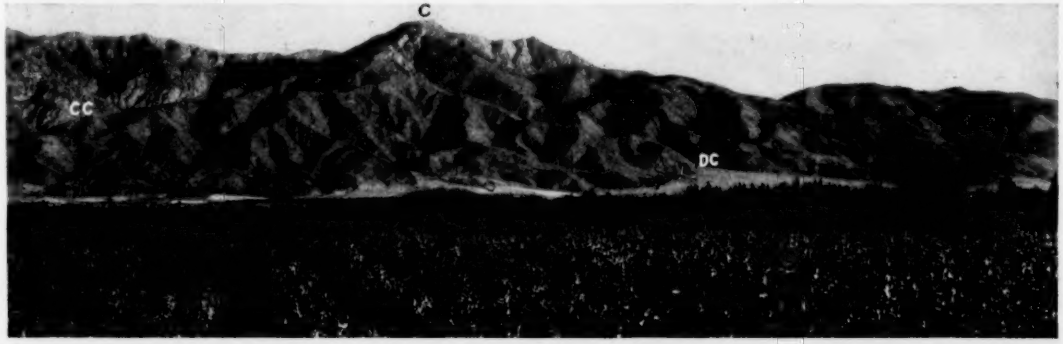

FIG. 2*b*.—View north, from Santa Fe Railroad near Cucamonga. *C*, Cucamonga Peak; *CC*, Cucamonga Canyon; *DC*, mouth of Deer Canyon.

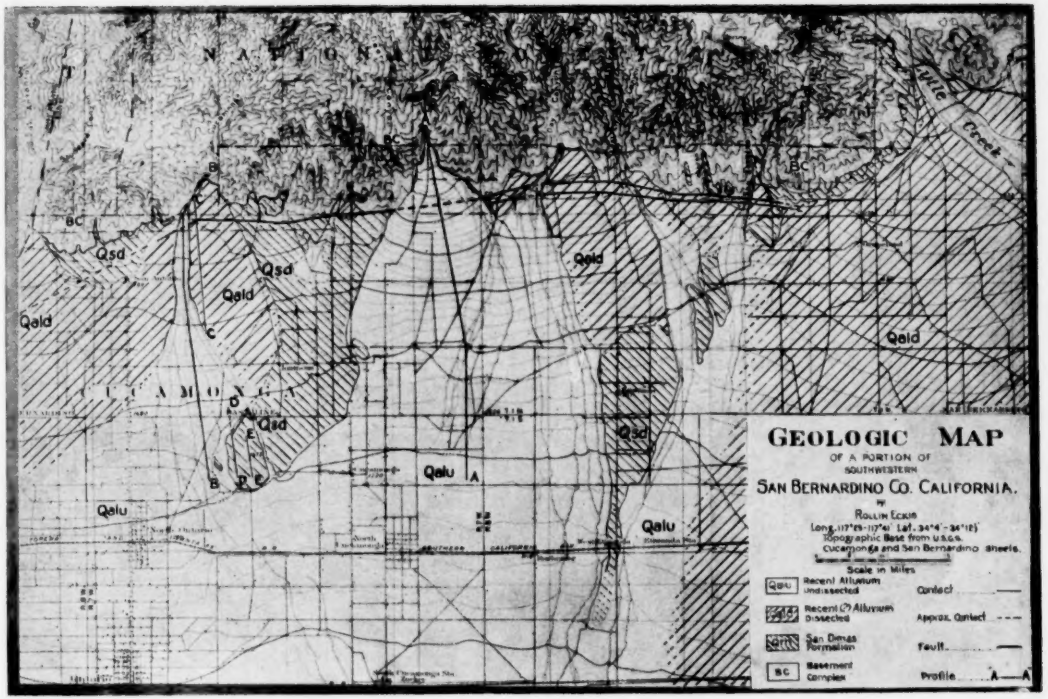

FIG. 3.—Geologic map of a portion of southwestern San Bernardino County, California

tapers down until at Lytle Creek it has practically disappeared. For a few miles west of Cucamonga canyon the scarp strikes approximately south 65° west, thus forming with the main portion an obtuse angle opening south.

THE CUCAMONGA SCARP

Recent movement has occurred on the two faults of the Sierra Madre fault zone which are shown in Fig. 3. Relative uplift on the northern side has produced scarps, which are either entirely in al-

FIG. 4.—The mouth of Cucamonga Canyon from the southwest, showing about 1½ miles of mountain front. *ABCD*, fault scarp; 1, 2, 3, alluvial surfaces.

luvium or between bed rock on the north and down-dropped alluvium on the south. The northern fault is the more continuous, and its surface expression will be called the Cucamonga scarp because of its excellent development at the mouth of Cucamonga canyon.

Figure 4, showing the mouth of Cucamonga Canyon, gives an idea of the characteristics of the scarp. The low 10-foot scarp *AB* crosses the most recently dissected alluvial surface (2) and evidently records the last uplift along this line. The scarp from *B* to *C* is 60–75 feet high and separates alluvial surface (1) from (2). It is due in part to

one or more uplifts previous to that producing *AB*. The scarp from *D* eastward to Deer Fan (Fig. 5) is from 200 to 250 feet high. It separates alluvium from bed rock. This portion of the scarp, protected from planation by the major streams, probably owes its greater height to a longer series of uplifts than is recorded by the scarp crossing Cucamonga Fan. Across Deer Fan (Fig. 5) the scarp is absent, but can be seen again abruptly terminating the bed-rock spurs east of the canyon (extreme right of Fig. 5). Here it is inferred

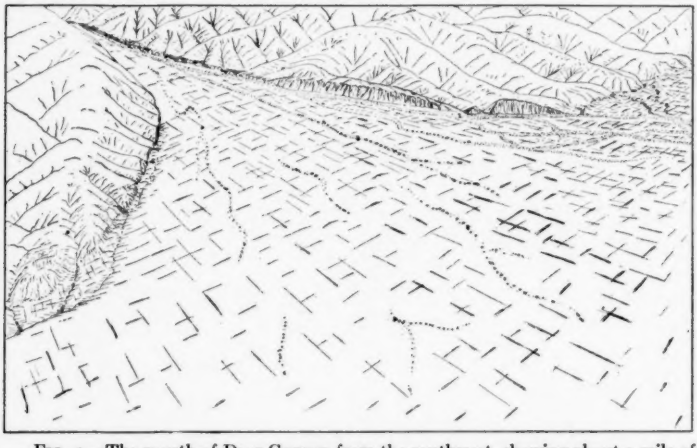

FIG. 5.—The mouth of Deer Canyon from the southwest, showing about a mile of mountain front.

that the actively depositing Deer Creek has planed off or buried even the most recent scarp across the fan surface.

Two special features developed along the scarp are worthy of mention. The "Block Hill" at *D* (Fig. 4) exposes 50 feet of alluvium overlying about 200 feet of bed rock exposed above the downdropped alluvial surface. The gravels have been tilted so that at the Cucamonga scarp they dip about 15° NE. (toward the mountains). The alluvial surface on top of the hill slopes about 5° north. Nearer the mountains this surface first flattens and then rises as a south-sloping cone remnant into a ravine mouth. Discrepancy between the dips of the gravels and the gravel surface indicates planation during tilting.

A second similar feature has been developed on Day Fan. A part of the fan surface above the Cucamonga scarp has been tilted so that it slopes south less than 1°. The adjacent normal fan slope is 5°. The resulting scarp is 100 feet higher where the tilt has taken place than elsewhere upon the fan. The gravels upon the planed-off surface of the Block Hill are decomposed and a red soil has developed. Those on the tilted surface of the Day Fan are fresh. This shows that the two local tilts are of different ages.

The scarp features shown in Figures 4 and 5 are characteristic of the Cucamonga scarp from San Antonio Canyon to the eastern end of the range. The scarp is always absent across present washes and fan surfaces, low across recently dissected alluvial surfaces, and high along the bed rock between the major alluvial fans.

The range front roughly parallels the Cucamonga scarp, but lies nearly ½ mile north of it. The two are separated by a dissected range-base terrace. This terrace can be seen at the extreme right side of both Figure 4 and Figure 5, where it is marked by flattened spur slopes. No important east-west faults were found in the bed rock north of the Cucamonga scarp. If the terrace were the result of faulting on the mountain front, the spurs should be displaced in the manner shown by Davis[1] for the Sierra Madre region 30 miles to the west. But the range-base terrace has a slope more nearly parallel to the surface of the adjacent down-dropped alluvium than to the slope of the range-front spurs. Therefore it is concluded that this terrace is probably a denuded suballuvial bench, and that the range-front scarp has receded from the fault at the Cucamonga scarp as a result of cutting of the bench by planation of the streams issuing from the mountains.

The fault plane corresponding to the Cucamonga scarp was not seen east of San Antonio Canyon, but the northward bend of the fault trace across the higher portion of Day Fan (Fig. 3) suggests normal faulting. However, at the mouth of Live Oak Canyon a short distance west of San Antonio Canyon, a steep (84°) reverse fault brings alluvium against bed rock. The surface expression of this fault appears to be a continuation of the Cucamonga scarp.

[1] W. M. Davis, "The Rifts of Southern California," *Am. Jour. Sci.*, Vol. XIII (1927), p. 59, Figs. 1, 2.

Uplift of the mountain mass east of San Antonio Canyon appears to have occurred principally along the line of the Cucamonga scarp. The physiographic expression of the series of displacements which produced the Cucamonga scarp and its lesser companion is so marked, and in such contrast to the dissected mountain front to the north, that it seems safe to assume that uplift of at least the eastern portion of the San Gabriel Range has been recently renewed after a pause and may still be in progress.

ALLUVIAL FANS

The recent alluvium.—Undissected alluvium at the mountain front is confined to narrow washes,[1] often incised between alluvial surfaces. It gradually spreads downstream into alluvial fans[2] which coalesce to form a *bajada* undissected to the vicinity of the Santa Ana River. The gravels strewn upon the present surfaces of deposition are Recent and have been mapped as undissected Recent alluvium (Fig. 3). The boulders and other rock fragments upon many of the trenched alluvial surfaces are also practically unweathered. The interval since deposition of these fresh gravels evidently has been relatively short, and hence they have been mapped as Recent (?) dissected alluvium. The trenched fresh deposits are exposed principally upon San Antonio, Cucamonga, Day, and Lytle fans.

The constituents of the gravels are principally gneissic or granitic in character, with occasional limestone, schist, and volcanic fragments present. These are exactly the materials of the San Gabriel range, the obvious source of the sediments. The fan deposits are poorly sorted and indistinctly bedded. A mechanical analysis of material from San Antonio Wash by A. O. Woodford[3] is probably characteristic of the fine fanglomerate.

The size of the fragments decreases less rapidly away from the

[1] The word "wash" is commonly used to denote a broad, gravel-strewn channel of an intermittent stream.

[2] The term "alluvial cone" is commonly used for a steep surface, and "alluvial fan" for a relatively flat surface. In this paper "cone" will refer to the small, steep alluvial piles built by minor streams along the mountain front, and "fan" to the large accumulations of the major streams.

[3] A. O. Woodford, "The San Onofre Breccia: Its Nature and Origin," *Univ. Calif. Publ. Bull. Dept. Geol. Sci.*, Vol. XV (1925), pp. 250, 254.

fan apex upon the larger fans than upon the smaller ones. This is shown in Table I.

The fresh gravels are spread as a thin veneer 10, 20, or 30 feet thick over older weathered alluvium. This is indicated by numerous observations of wells, pits, and stream cuts, widely spread over the upper parts of the fans, 10 miles or less from the mountains. The veneer may reach a maximum thickness of one or two hundred feet 2–5 miles from the larger fanheads, and may be even thicker on some parts of Deer Fan.

TABLE I*

SIZES OF FRAGMENTS ON FANS

Fan	At Fan Apex (Inches)	Slope Angle	2½ Miles from Apex (Inches)	Slope Angle	5 Miles from Apex (Inches)	Slope Angle
Lytle	87	1° 40′	54	1° 35′	30	1° 00′
San Antonio	69	2° 40′	54	1° 58′	26	1° 30′
Cucamonga	90	2° 45′	30	2° 20′	22	1° 25′
Day	112	5° 45′	21	2° 30′	13	1° 05′
Deer	157	9° 05′	19	2° 33′	8	0° 59′

* Each value given is the median of the lengths of the ten largest fragments found in a distance of 50 yards along the wash.

Alluvial surfaces in this district can be divided into two groups: (1) the surfaces of minor cones whose débris has been derived from the Sierra Madre scarp only, (2) the surfaces of major fans whose débris has come from the big canyons that extend far into the range.

The cones are found only near the mountain front in the triangles between the major fanheads. They are nearly all dissected, with active streams spreading out a thin veneer of fresh and reworked materials at their bases, usually upon the surfaces of the major alluvial fans. These small cones have sharply concave longitudinal profiles, steep grades near their heads, and lower grades than the major fans at distances of a mile or two from the mountains.

The major fans extend their surfaces from the mountains practically to the Santa Ana River, into which their flood waters drain. The heads of these fans are generally several miles apart, allowing space for complete development of the upper parts of the fans. The heads of the present fans vary in elevation roughly with their slope angles and in the inverse order to the areas of their watersheds.

This is shown in Table II, for which elevations and areas were taken from the U.S. Geological Survey Quadrangles. Figure 6 shows that

TABLE II

FANHEAD ELEVATIONS AND GRADES

Fan	Elevation of Stream at Fanhead	Stream Grade at Fanhead	Area of Watershed in Square Miles
Lytle	2,050′	1° 40′	47.9
San Antonio	2,200′	2° 40′	26.2
Cucamonga	2,250′	2° 45′	10.6
Day	2,600′	5° 45′	4.9
Deer	3,000′	9° 5′	3.4

a large fan has a profile with less concavity than a smaller fan with a higher grade.

During the flood of February 16, 1927, the processes of stream distribution were seen in action upon the alluvial surfaces near the

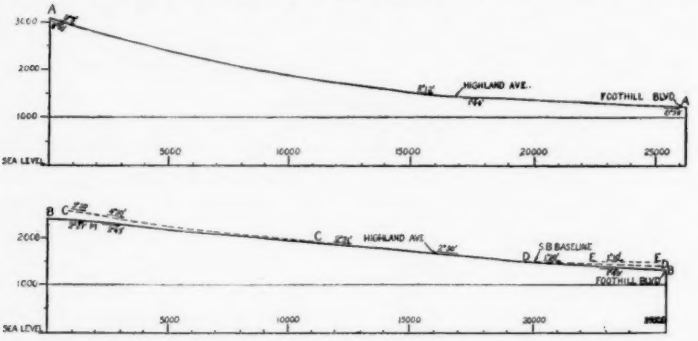

FIG. 6.—Longitudinal profiles of fan surfaces and fan remnants. *AA*, Deer fan; *BB*, Cucamonga fan; *CC*, dissected Cucamonga fan; *DD*, Red Hill terrace; *EE*, Red Hill mesa. See Figure 3 for locations of profiles. Data from transit stadia traverses.

mountain front. The flood waters flowed in shallow channels cut below the general surface of the fan. When a previously confined stream suddenly spread out on the fan, by overflow or otherwise, it dropped part of its load. The gradient was thus steepened below the point of deposition and lessened above that point. Lessening of the

grade by piling up of débris accelerated the deposition already begun, and the result was that the stream unloaded at this point, building a low débris dam across its channel. At first the water was distributed over the whole surface of the dam. Then, since a large part of the load struck the dam's center, this portion was built up until the water was forced to the sides. The stream became weaker in the middle and finally was divided into two streams, or occasionally merely diverted to one side. Similar débris dams across channels occur frequently and appear to be the chief distributing agents upon these fans. The enormous boulder pile at the mouth of Deer Canyon, 20 feet high in the center and with crescent horns pointing south, may have had a similar origin.

The San Dimas alluvium.—Dissected alluvium with decomposed gravels and red, brown, or yellow color commonly occurs as high fan-head remnants and as isolated or nearly isolated midfan mesas. These decomposed gravels were first described by Mendenhall,[1] who called them "earlier alluvium." The term San Dimas formation is here proposed to designate these continental deposits. The type locality is at San Dimas, 5 miles west of Claremont, and thus west of the limits of Figure 3. Here, beneath a cut terrace in a branch ravine of Walnut Creek, 300 yards southeast of the Southern Pacific station at San Dimas, Professor A. J. Cook, of Pomona College, found molar teeth and other portions of a skeleton of *Elephas imperator(?)* in a reddish-yellow silty sandstone which is interbedded with brown fanglomerates. The beds parallel the dissected fan surface 60 feet above the point where the fossil was found. This fan surface conforms in position and character to those of the San Dimas formation in the area here described.

The degree of weathering at different places varies, and occasionally it is difficult to distinguish San Dimas from Recent gravels. Experience suggests that San Dimas outcrops can be recognized by the fact that their gneissic fragments crumble in the hand.

Variations in lithology are irregular, but in general there is relative increase in thickness and number of coarse beds in the direction

[1] W. C. Mendenhall, "Ground Waters and Irrigation Enterprises in the Foothill Belt, Southern California," *U.S. Geol. Survey Water Supply Paper 219* (1908), pp. 10–12.

of the fan apex, and a relative increase in the number and thickness of fine beds toward the fan margins.

Wells observed during drilling indicate that the greatly weathered red soil of the San Dimas formation is the result of long exposure to surface weathering. It may be frequently repeated in depth, but often with fresh, gray gravels between.

The San Dimas alluvium, where exposed, is generally undeformed. However, a noteworthy exception appears at Red Hill (Hill 1472 of Fig. 3, near Cucamonga). Mendenhall[1] noted doubtfully north-dipping beds in a tunnel under Red Hill. A stream cut 50 feet long, at the east base of Red Hill, also exposes beds dipping north, the angle being 10°. Contacts with the overlying undeformed beds are obscured by surface soil and slides. However, a few hundred feet upstream peaty silts with an original south dip are interbedded with coarser materials. These swamp deposits may have accumulated behind a tilted surface. The deformed gravels have been covered by at least 150 feet of undeformed sediments (shown by higher remnants) which have since been dissected to the present stream bed. Although tilting during accumulation of the Red Hill gravels is strongly indicated, the origin of the surfaces of Red Hill and its neighbors is not related to that tilting.

DISSECTION OF ALLUVIAL FANS

The alluvial fans of this region are quite generally dissected. The dissections occur principally in two areas.

1. *The fanhead area*—Many of the fanheads are trenched by the present streams, which are depositing farther out. Some of these trenches end downstream at the fault scarp. Others continue farther, become shallower downstream, and finally fade out (Fig. 4).

2. *The outer fan area.*—Several mesa remnants of fans are found at distances of several miles from the mountain front. As the mesa slopes are flatter than those of the present fans, the remnants in some cases are partially buried at their upper ends. The map (Fig. 3) suggests this, and it is shown more clearly in the profiles (Fig. 6).

[1] *Op. cit.*, pp. 34–35.

POSSIBLE CAUSES FOR DISSECTION OF ALLUVIAL FANS

Factors which contribute to the dissection of alluvial surfaces may be classified as follows: (1) An increase in the volume of storm water, due to increased precipitation, capture of part or all of an adjacent watershed, or destruction of vegetation by grazing in recent years, (2) a decrease in the available load, as by exposure to erosion of a more resistant type of rock, or by decrease in the rate of weathering through other causes, (3) diastrophic movements which uplift one portion of the fan with respect to another, or which increase the slope of the whole fan or a portion thereof, (4) lowering of the trunk stream or lateral migration of the trunk stream into the fan base, and (5) dissection in the normal course of the cycle. The last cause operates when the grade of the stream above the fan becomes so low (probably considerably lower than that of the alluvial fan grade) that the stream is not fully loaded when it starts down the slope of the fan.

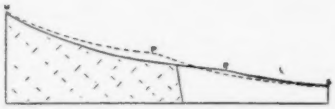

FIG. 7.—Diagram showing the longitudinal profile of a fanhead. *MPS*, stream course before trenching; MP_1S, stream course after trenching.

In connection with this fifth, sometimes ignored, cause for dissection of alluvial surfaces, a schematic outline of the normal stream and fan development, following an uplift, may suggest the probable process by which an alluvial fanhead is dissected normally by the stream that built it.

When the stream above the fan becomes essentially graded, the point of distribution (at the head of the fan) becomes the critical point (*P* of Fig. 7). Below this point the water loses power by subdivision as well as by seepage, just as the "water which carries the débris of a district loses power by subdivision toward its sources."[1] As the distributaries are loaded, they will build up the fanhead until the grade of the fan below the point of distribution is steeper than that of the stream above this point. The accomplishment of this develops a convexity in the stream profile about the point of dis-

[1] G. K. Gilbert, *Report on the Geology of the Henry Mountains* (1877), pp. 109–10.

tribution (P). This point slowly moves upstream. In humid or moderately arid regions this rise of the point (P) is too slow to counterbalance the reduction of grade in the mountain canyon. The result is an increasing convexity where the canyon grade and fanhead slope meet (profile MPS, Fig. 7). But a time will be reached when flood waters will cut a single channel through the steeper fanhead, which will carry all the water. Confined to a single channel, the stream no longer loses power by subdivision and must cut to a lower grade. Since the fan surface beyond the apical convexity becomes flatter as it spreads out upon the basin floor, the grade of the new channel will bring it out onto the fan surface at a lower level. Distribution must then take place at this point (P^1). The rejuvenation travels headward, cutting a trench into both bed rock and the earlier fanhead, and adjusting the stream to its new distributing point (profile MP^1S, Fig. 7). The former process is then repeated. P^1 moves upstream, and the dissected fanhead is removed by lateral planation. When the critical convexity is again reached, the point of distribution will be moved down the fan slope to a still lower level. These dissections will become longer and more shallow as the fan slope becomes less concave, and in an open drainage finally must reach the trunk stream or other outlet. The fan stage may then be replaced by a flood plain. If this theoretical process occurs in fact, evidences of its different stages should be observable in actual alluvial fans.

DISSECTED ALLUVIUM IN THIS AREA AND THE PROBABLE CAUSAL RELATIONS

Displacement of alluvial cones by the Cucamonga uplift.—The general effect of this uplift upon the alluvial fans was described briefly under "The Cucamonga Scarp." All the cones in this area have been cross-faulted. This can be observed for all except Deer Fan, and is inferred for it. All major streams except Deer Creek have since cut through the edge of the uplifted mountain block to approximately their previous grades.

Recently dissected fanheads.—We have here five alluvial fans, four of which in Recent time have had their fanheads trenched independently of faulting. The trenches in the four cases did not develop simultaneously. San Antonio Creek has so recently cut into its fan

that the maximum depth of the trench is only about 15 feet, and convexity at the apex has not yet been destroyed. Yet this is truly a dissecting trench, for it locally cuts entirely through the Recent alluvium.

Cucamonga Fan (Fig. 4), adjacent to San Antonio on the east, clearly shows two dissected surfaces (1 and 2, Fig. 4). Much higher than any of these is a small terrace remnant of older alluvium, 550 feet above the present stream. Surface 1 is terminated on the south by the Cucamonga scarp. Surface 2 is cut through by a stream trench to a maximum depth of 150 feet and a length of 1½ miles, though Cucamonga is a much smaller stream than San Antonio.

Deer Fan, east of Cucamonga, is undissected. It is the smallest major fan and the steepest; its stream has the shortest course; it flows from one of the highest points in the range and it receives large tributaries to the very mouth of its canyon. As a result this stream has only developed a grade in its canyon as low as that of its fanhead for a distance of a few hundred feet above the fan apex. The fanhead slopes 9°. The mountain canyon reaches a grade of 11° 1½ miles upstream.

The dissected Day alluvial fan surfaces are complicated by the presence of two fault scarps crossing them. The present stream trench dies out on the fan surface a short distance below the lower scarp.

Lytle Creek, the largest stream and the least steep, has developed a Recent trench, which at the canyon mouth is only 8–15 feet deep. The cut becomes deeper downstream for a distance of 6 miles, until its west bank is about 75 feet high, its east bank 20 feet high. The cut then gradually decreases to zero at a point about 3 miles farther from the canyon mouth and within a short distance of the junction with the Santa Ana River. The peculiar character of the cut may be due in part to the fact that Lytle Creek follows a regional fault line, with consequent possible differential vertical movement of the two banks. Moreover, a faint anticlinal flexure on the west side is suggested by a slight and doubtful convexity of the old fan surface. But more important is the steepening of the Lytle Creek grade just above the maximum cut and just above the mouth of the tributary Cajon Creek, so that it is apparent that the deeper part of the cut

is chiefly due to the junction of these streams, which formerly flowed separately to the Santa Ana River.

Origin of the fanhead trenches.—A peculiarity of the Lytle dissection has just been explained. It remains to consider the fanhead trenches in general.

The hypothesis of destruction of headwater vegetation is inadequate to explain the dissection, for fire effects are transitory and the vegetation has remained practically untouched by grazing or other indirect human influences. Exposure to erosion of a more resistant type of rock as a cause for dissection is not probable because the bed rock is so uniformly variable. A general tilt or warp must be ruled out, at least as the sole or principal cause, since the dissection of the various fans usually reaches a maximum at the fanheads and is so extremely unequal there.

An increase in the volume of water with respect to the available load, if brought about by a climatic change, would presumably result in a general rejuvenation in the adjusted stream systems, accompanied by fanhead trenching. Since neither dissection of all the fanheads nor general rejuvenation of the stream systems has occurred, climatic change is probably not the sole or principal cause. A study of the U.S. Geological Survey topographic maps shows that there have been no increases in volume of water due to capture in Recent time.

There remains one hypothesis which apparently will explain these Recent trenches, that is, that they represent the lowering of the point of load distribution to accommodate a normally lowered stream grade above the fan apex. This hypothesis fits all the known facts, and, in particular, explains the trenching of the larger fans, while the smallest, Deer Fan, remains entire. Moreover, dissection rather certainly did not begin at the same time in all the trenched fanheads. Both Lytle and San Antonio creeks may have trenched their fanheads several times and then planed off the dissected portions. Terraces outside the limits of Fig. 3 indirectly suggest this.

The various fans appear to be at different stages of development. In this area each fan has begun its growth upon a down-faulted block. As the young fan grows its apex gradually moves upstream (Deer stage). The stream grade above the fan decreases and finally

the fanhead is trenched, apparently without necessity of a climatic or diastrophic change (Cucamonga stage). Recurrent dissection of the fanhead and subsequent removal of the dissected portion by planation then probably occurs. This accompanies the lowering of the stream grade above the fan. Thus the intermediate or distal part of the fan is being built up, but the apex is being dissected. With each succeeding dissection the trench more nearly approaches the trunk stream. Finally the dissection may be expected to extend entirely across the fan (post-Lytle stage). Then building up of the fan surface will be at an end, and will be followed by the gradual destruction of the last-formed fan surface. The whole fan development is here probably but an incident in the geographic cycle.

The dissected San Dimas cones.—Along the mountain front between the major fanheads numerous small dissected cones are found. These cones are relatively steep near their apices, but flatten out rapidly and terminate at the margins of the major fans. Dissection of many of these cones has been in progress so long that they have developed a typically weathered red soil upon their surfaces. The varied character of these San Dimas cone remnants indicates that they have not resulted from a single cause, but are the product of several different factors. Some remnants, as at the Block Hill (p. 5), lie upon the bed-rock bench north of the Cucamonga fault. These are, in part at least, dissected due to the Cucamonga uplift. Discrepancy between the surface slope of the Block Hill and the dip of fanglomerate beds in the hill shows that planation occurred during tilting. Later uplift caused the cone to be dissected. We have here some measure of the relative times required to produce a weathered red soil and to reduce a fault scarp. The Cucamonga scarp, though dissected by streams from the mountains, still stands out as a bold physiographic feature. Formation of a weathered soil upon a gravel surface has required a relatively short time.

A few San Dimas cone remnants are found which cross the Cucamonga scarp with no more displacement than adjacent Recent (?) gravel surfaces have suffered. Evidently their dissection was not initiated by faulting. For the same reasons which apply to trenching of Recent fanheads these older remnants are not due to tilting (except locally), change of rock type, or lowering of the fan base by any

cause. The streams dissecting these cones have relatively low headwaters and hence have cut down to lower grades at their mouths than that of Deer Creek. Dissection may be a normal incident in the cycle, but the similarity and great dissection of the cones makes inapplicable the criterion used for the Recent fanhead trenches. Climatic change during late Pleistocene time[1] was probably a factor.

The older alluvial remnants along the mountain front have had a complex history. Some are the direct result of uplift with local tilting; others probably owe their origin to lowered stream grades; and the whole series may have been considerably modified by climatic change.

Fanhead trenches elsewhere.—It seems probable that in most regions where alluvial fans occur there will be found fanhead trenches, fading out below, though under conditions of great aridity mountains may simply and continuously be buried in their own débris.[2] An examination of the available literature shows that such trenches have been described from three or four widely separated regions. Drew long ago observed this type of dissection in the Upper Indus Basin.[3] Pumpelly, Davis, and Huntington[4] seem to have found similar features widespread in Central Asia. In the American Southwest the phenomenon has been observed both in alluvium[5] and in bedrock "pediments,"[6] with trenching up to 250 feet in depth. The phenomenon is widespread in this region, with noteworthy undescribed examples along the north margin of the San Bernardino Mountains and the northeastern margin of the Santa Ana Moun-

[1] That a climate moister than the present prevailed in Southern California during at least a portion of the Pleistocene is shown by the fossils. See, for instance, the paleobotanical evidence presented by R. W. Chaney and H. L. Mason, *Science*, n.s., Vol. LXVI (1927), pp. 156–57.

[2] A. C. Lawson, "The Epigene Profiles of the Desert," *Univ. Calif. Publ. Bull. Dept. Geol.*, Vol. IX (1915), pp. 30–33.

[3] Frederick Drew, "Alluvial and Lacustrine Deposits and Glacial Records of the Upper Indus Basin," *Quart. Jour. Geol. Soc.*, Vol. XXIX (1873), p. 454.

[4] R. Pumpelly, W. M. Davis, and E. Huntington, "Explorations in Turkestan," *Carnegie Inst. Wash. Publ.*, Vol. XXVI (1905).

[5] A. C. Lawson, "The Geomorphogeny of the Tehachapi Valley System," *Univ. Calif. Publ. Bull. Dept. Geol.*, Vol. IV (1906), p. 449.

[6] Kirk Bryan, "Erosion and Sedimentation in the Papago Country, Arizona, with a Sketch of the Geology," *U.S. Geol. Survey Bull. 730* (1922), pp. 60–65.

tains, both in Southern California. Cotton[1] has described terraces in New Zealand which are considered to be due to the normal degradation of alluvial fans. Stream-terrace profiles in South America described by Penck[2] suggest that fanhead trenches may exist there also at the mountain margins.

The dissection of alluvial fans was discussed by Baker[3] as possibly a special case of the long-recognized normal dissection of flood plains under constant conditions,[4] but apparently Baker was not considering fanhead trenches.

Midfan mesas.—There are three principal areas of midfan remnants, all of San Dimas age: (1) Indian Hill and Claremont, (2) the Red Hills, and (3) Etiwanda and vicinity.

Indian Hill and Claremont lie just west of the limits of Figure 3. Indian Hill is a mesa, $\frac{1}{3}$ mile long, and about $\frac{1}{4}$ mile wide. It is elongated parallel to the radius of the fan, and has a maximum slope of 1° 23′ (S. 40° W.) away from the apex.[5] The slope of the present fan about the hill is 1° 55′. Consequently the mesa is only about 15 feet high at its northeast end, but rises to 40 feet above the present alluvium at its southwestern end. The size of fragments in the Indian Hill fanglomerate is less than that of the fragments in the Recent wash. This corresponds to the difference in grades of the two surfaces, and suggests that the Indian Hill surface has not been appreciably tilted since its formation. There are several similar but lower mesas of the San Dimas formation in the town of Claremont, just south of Indian Hill.

The Red Hills (Red Hill and its neighbors), 4 miles southeast of the mouth of Cucamonga Canyon, bear two dissected fan surfaces. The upper Red Hill surface forms the mesa top of Red Hill (Hill

[1] C. A. Cotton, *Geomorphology of New Zealand*, Part I (1922), p. 255.

[2] Walther Penck, "Der Südrand der Puna de Atacama," *Abh. d. mathphys. Kl. d. sächs. Akad. d. Wiss.*, Bd. 37 (1920), p. 399.

[3] C. L. Baker, "Notes on the Later Cenozoic History of the Mojave Desert Region in Southeastern California," *Univ. Calif. Publ. Bull. Dept. Geol.*, Vol. VI (1911), pp. 374–77.

[4] W. M. Davis, "River Terraces in New England," *Bull. Mus. Comp. Zoöl. Harvard Coll.*, Vol. XXXVIII (1902), pp. 281–346; Emil Gogarten, "Über alpine Randseen und Erosionsterrassen," *Petermann's Mitth. Ergänzungsh. 165* (1910), pp. 44–50.

[5] Determined by Professor Edward Taylor, Pomona College.

1472 of Fig. 3) and the two hills at approximately the same elevation, one mile northeast. This surface has a slope of 1° 10′ away from the Cucamonga fan apex (Fig. 6). The surface is more maturely dissected than the Indian Hill surface.

The lower Red Hill surface forms a terrace about 125 feet below the upper surface and around its west, north, and east margins. It is much more extensive than the mesa. The profile (Fig. 6) shows it to have a maximum true slope of approximately 1° 30′ on either side of Red Hill (20′ more than that of the mesa). It reaches a height of about 40 feet at its southern end, where it is cut off by a stream scarp. Followed north from Red Hill, the height of the terrace decreases and the western side of the surface passes under the Recent alluvium a few hundred feet north of the San Bernardino base line. The flat top of Lone Hill, 1,000 feet west of Red Hill, fits perfectly the lower Red Hill surface extended. Northeast of Red Hill the lower surface can be followed continuously around the eastern margin of Cucamonga Fan even to the mountains. It is only slightly eroded and is a part of the abandoned surface to which the dissected San Dimas cones along the mountain front belong. No doubt most of the corresponding Cucamonga and Deer fan surfaces have been buried or removed, but the less active streams between the two larger fans have been unable to destroy the older surface. The profiles of the upper and lower Red Hill surfaces (Fig. 6) are possible profiles of earlier fan stages in the present cycle of deposition.

The Etiwanda surface, as shown on the map (Fig. 3), emerges from under the Day fan and extends south about 4 miles, finally becoming lost in wind-controlled topography out at the fan margin. It is undercut only on the east, by the waters of the Lytle fan. This surface diverges very slightly from that of the Recent alluvium, and at no point is there more than 20 feet difference in elevation between the two. The Etiwanda surface is probably younger than either the lower Red Hill or Indian Hill surfaces, for it has not so completely developed the typical red soil. East of the main Etiwanda mesa there are several isolated remnants of this surface, which are bounded by steep stream scarps.

Origin of the midfan mesas.—These mesas were regarded by Mendenhall[1] as protruding hills of an earlier alluvium, elsewhere

[1] *U.S. Geol. Survey Water Supply Paper 219* (1908), pp. 12, 34.

deeply buried by a later alluvium. But it has been shown in the foregoing pages that the Red Hill terrace extends unbroken to the mountain margin, that its profile and that of the mesas are exactly such as might be expected for slightly earlier stages of the present compound fan surface, and that the San Dimas weathered alluvium is found generally only a few feet below the surfaces of the active fans. The lower Red Hill fan surface is dissected at the fanheads, but farther out on the fan (Fig. 6) it is merely overlapped by Recent sediments, and again at Red Hill it is being eroded. It follows that the mesas are fan remnants which have never projected much higher above their surroundings than they do today.

The possible causes that must be considered for the dissection of the earlier Cucamonga and San Antonio fans to form the present Red and Indian Hills are limited by the nature of the dissection. Since (1) the Red Hill terrace and Indian Hill mesa grades are but a fraction of a degree less than those of the present fan, and the Red Hill mesa grade but a further fraction less than that of the terrace, and since (2) the terrace remnants slope away from the respective fanheads, the Red Hill and Indian Hill surfaces are probably untilted fan slopes. These surfaces diverge downstream from the present alluvial fan surfaces. Therefore their dissection is due to causes resulting in a relative lowering of the fan bases south of these remnants. This could be accomplished in two general ways: (1) By lowering of the trunk stream (Santa Ana River) or by lateral planation of the trunk stream, and (2) by relative uplift of the mesas.

An examination of the topographic maps of the U.S. Geological Survey shows that lateral planation by the Santa Ana River has not been a cause. In fact, the displacement of the river's course seems to have been south rather than north. Lowering of the trunk stream would have caused continuous channels to be cut from the river to the mountains. If this had been the case there would be remnants at levels corresponding to the Red Hill mesa around the margins of the basin in such places as the Jurupa Hills south of Etiwanda or the San José Valley west of Pomona, where there have been no active streams to remove them. There are no such terraces more than 10 feet high. Therefore the cause is probably not a lowering of the channel of Santa Ana River.

We have the alternative of an uplift. If this has occurred it has

been practically without tilting, since the Red Hill and Indian Hill surfaces are not appreciably disturbed. A vertical fault or monoclinal uplift between Red Hill and the Santa Ana River seems to be the most probable explanation for these remnants. The two surfaces may indicate two separate uplifts.

We know that the line of uplift must lie south of Indian and Red hills, and north of the Santa Ana River. An eastward extension of the fault which follows the south side of the San José Hills west of Pomona,[1] would carry it across this area. This fault has a very recent physiographic expression in the San José Hills section. Notched spurs mark the fault trace along the foot of the eroded scarp, the base of which has not yet receded appreciably from the fault. Although there is direct evidence that this fault does not itself continue east out into the alluvium, the uplifted fan remnants north of its projected line suggest that another member of the same *ENE* system is present south of Red Hill, and that uplift along it has caused dissection of the upthrown alluvium, with resulting remnants of fan surfaces above the present surface of deposition.

The long, slightly dissected Etiwanda fan-base remnant offers a problem in connection with the possible extension of the San José fault system. This surface is not terminated by a scarp, but continues south across the projected line of the fault without displacement. The fault either dies out west of this surface, or the surface has been formed after uplift along the fault. The slight degree of dissection and the lack of a typically decomposed red soil both suggest that it is of later origin than the lower Red Hill surface. If this be true it may be a post-uplift surface developed across the planed-off uplift.

CONCLUSIONS

The eastern part of the San Gabriel Mountain block has been differentially elevated some 4,000 or 5,000 feet above the neighboring block to the south. Renewed uplift (Cucamonga uplift) is evidenced by two scarps, 10–250 feet high, largely in alluvium, paralleling the main mountain front and lying nearly ½ mile in front of it. Nearly vertical faults are indicated. The scarps have been produced by a

[1] Walter A. English, "Geology and Oil Resources of the Puente Hills Region, Southern California," *U.S. Geol. Survey, Bull. 768* (1926), Plate I.

series of small displacements, so recently that their steep, slightly dissected fronts stand in marked contrast to the maturely dissected range-front scarp, which probably receded to its present position from the line of renewed uplift. Despite the slight dissection of these scarps some portions of them have been in existence long enough for the formation of a red soil and the rotting of gneissic débris.

A system of alluvial fans has developed along the base of the mountains concomitantly with the uplift of the range. Fan growth has not been a simple, continuous process. There are records of the partial dissection of the fans from late Pleistocene to the present time, but there is no evidence that all the fans were ever being dissected at any one time.

The fans have been dissected (1) at their apices, and (2) in midcourse. Dissection of the two areas does not appear to be causally related. Trenching of the fanheads by streams issuing from the canyons appears to be the result of two or three principal factors: (1) the Cucamonga uplift, (2) the normal reduction of the mountain stream grades, and perhaps (3) climatic change. The older midfan surfaces are deeply dissected and almost entirely removed by planation, probably due to a vertical displacement north of the Santa Ana River, of 200 or more feet.

Finally, the Recent fanhead trenches give evidence that here fan development is temporary, a mere incident in the geographic cycle.

A SKELETAL MODEL OF THE PRIMITIVE REPTILE *SEYMOURIA*, AND THE PHYLOGENETIC POSITION OF THAT TYPE

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ABSTRACT

A skeletal model of *Seymouria*, a primitive tetrapod, is described and figured, together with a life-restoration. *Seymouria* is to be considered a reptile rather than an amphibian, for it possesses many positive reptilian characters, while the amphibian structure of its otic region is that to be expected in the ancestry of the reptiles.

Seymouria baylorensis, a small cotylosaurian reptile from the Clear Fork Permian of the Texas red beds, was described by Broili in 1904, mainly on the basis of two skulls.[1] Later Williston[2] gave a detailed description of most parts of the skeleton, basing his account on a nearly complete specimen, while Watson[3] has added further to our morphological knowledge and discussed its relationships in detail.

Williston's work revealed many primitive features of the skeleton, while Watson, as a result of comparative studies, calls it emphatically "the most primitive known reptile." Indeed, so primitive is it that Broom,[4] while stating that "it certainly lets us know more of the primitive tetrapod structure than almost any other known type," considers it to be an advanced embolomerous amphibian rather than a true reptile, and Sushkin[5] also believes it to be an

[1] F. Broili, "Permische Stegocephalen und Reptilien aus Texas," *Palaeontographica*, Vol. LI (1904), pp. 1–120.

[2] S. W. Williston, "*American Permian Vertebrates*" (Chicago, 1911), pp. 48–67.

[3] D. M. S. Watson, "On Seymouria, the Most Primitive Known Reptile," *Proc. Zoöl. Soc.* (London, 1918), pp. 267–301.

[4] R. Broom, "On the Persistence of the Mesopterygoid in Certain Reptilian Skulls," *ibid.* (London, 1922), pp. 455–60.

[5] P. W. Sushkin, "On the Representatives of Seymouriamorpha from the Upper Permian of Russia, etc.," *Occas. Papers, Boston Soc. Nat. Hist.*, Vol. V. (1925), pp. 179–81; and "On the Modifications of the Mandibular and Hyoid Arches and Their Relations to the Braincase in the Early Tetrapoda," *Paläontologische Zeitschrift*, Vol. VIII (1926), pp. 309–21.

amphibian. It is without doubt the most primitive land vertebrate of which we have a comprehensive knowledge of the skeleton, and is hence of profound importance from the evolutionary and morphological viewpoints.

But despite our nearly complete anatomical knowledge of *Seymouria*, it has hitherto been difficult to visualize the general appearance of this reptile. No mounted skeleton exists, and there is

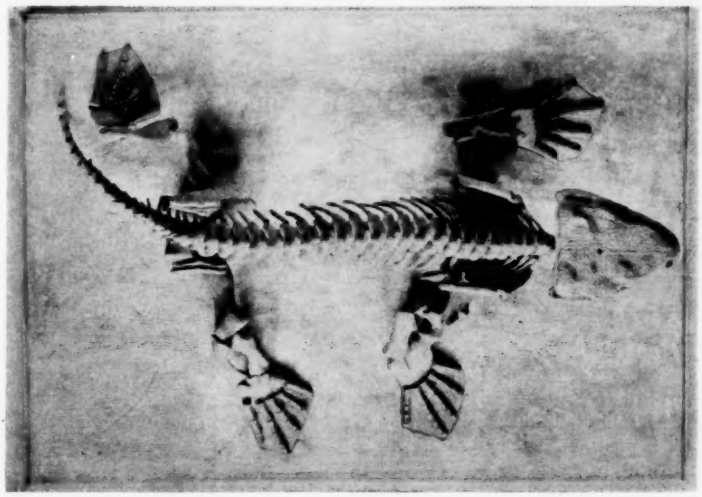

FIG. 1.—Model of *Seymouria baylorensis*, from above. ×⅓, approx.

only one nearly complete specimen (No. 663, Walker Museum, University of Chicago), which is, unfortunately, imbedded in so hard a nodular matrix that the bones cannot be freed from it. Williston has figured a restoration of the skeleton from above, Watson, a side view; but *Seymouria* has never existed for us in three dimensions.

The skeletal restoration here illustrated was undertaken some time ago at the instance of Dr. W. K. Gregory, curator of comparative anatomy in the American Museum of Natural History, while the writer was a member of the departmental staff, and was planned as part of an exhibit showing the evolution of the vertebrate skeleton. The model was based upon a study of the remains in Walker Mu-

seum and the American Museum and the published descriptions of Broili and Watson. The specimens varied slightly in size, and were reduced to that of the Chicago skeleton as a base. The parts were modeled in plasticene and were cast by Mr. Otto Falkenbach of the American Museum.

In the model, as figured, most of the primitive features of the skeleton noted by Williston and Watson are clearly visible (except, of course, certain cranial characters). The skull, which retains all

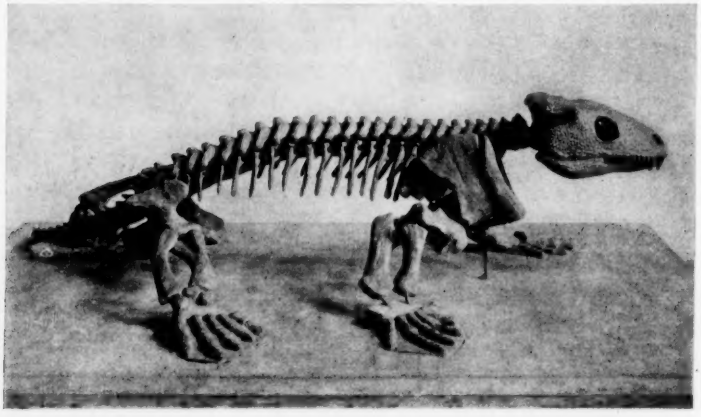

FIG. 2.—Model of *Seymouria baylorensis*, from the side. $\times\frac{1}{4}$, approx.

of the primitive tetrapod elements, is of a relatively high and narrow build, and is in marked contrast with the flattened type toward which the contemporary amphibians were tending. The orbits face laterally rather than dorsally; the pineal foramen of primitive tetrapods is visible between the two parietals. In the temporal region *Seymouria* (and its relatives) retains the typical otic notch of primitive amphibians—a unique character for reptiles.

The figures show clearly the shortened vertebral column of the animal, with complete true centra, and reduced intercentra (although they are larger than is usual in reptiles), the rudimentary neural spines, and especially the broad, convex neural arches with horizontal zygapophyses so characteristic of most of the cotylosaurs.

The ribs are continuous from the cervicals to the base of the tail, and typically have a capitular attachment to the intercentra, with tubercles attached to transverse processes of the arches. Those to which the muscles supporting the scapula are attached are typically enlarged. As mounted, the ribs are somewhat too vertically placed; those in the dorsal region should extend somewhat further laterally.

The limbs are of the short, clumsy-looking, but powerful type found in so many members of this fauna; seemingly a primitive

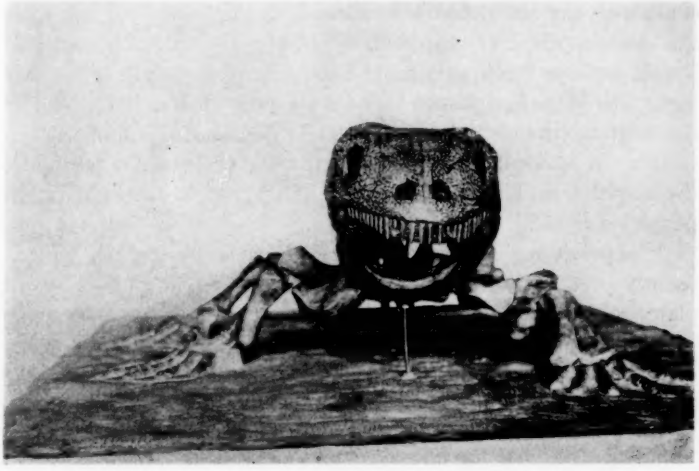

FIG. 3.—Model of *Seymouria baylorensis*, front view. $\times\frac{1}{2}$, approx.

character. The probable presence of a powerful musculature (processes for the attachment of which are especially prominent on the humerus) has led to the interesting but probably erroneous suggestion that some primitive reptiles were burrowing types. The proximal segments of the limbs are turned out horizontally at nearly right angles to the body, giving a broad but short stride. This seemingly awkward pose has given rise to the conception that forms with this type of skeleton may have been crawling types, their bellies dragging on the ground (see, for example, Lull's restoration of Limnoscelis);[1]

[1] R. S. Lull, "Organic Evolution" (1917), p. 499, Fig. 150.

but what we know of the footprints of reptiles and amphibians of this general period shows that this was not the case; the powerful musculature apparently sufficed to keep their bodies clear of the surface. A suggestion is given of the sinuous curvature of the vertebral column characteristic of primitive tetrapods, a feature which aids the advancing limb to gain a more anterior position than its musculature and articulations alone would permit,[1] and which Watson[2] suggests is an inheritance from crossopterygian ancestors.

The shoulder girdle is placed almost immediately behind the skull, with the nearly complete absence of the "neck," as is usually the case in primitive amphibians and reptiles;[3] in fact, the girdle should perhaps be slightly more anteriorly placed than is the case here. The long clavicle can be seen ascending the anterior edge of the scapula (the cleithrum is absent in *Seymouria*, one of the few features in which it is not primitive), while the anterior portion of the long-stemmed interclavicle, of reptilian type, is visible below the (single) coracoid.

The pelvic region shows the single expanded sacral rib, the anteriorly-posteriorly elongate ilium, and the solid pubo-ischiadic plate.

The humerus is of the primitive tetrahedral type, with prominent muscular attachments; on the right side, from above, the entepicondylar foramen is visible. The femur is also short and stout; on the left side the "fourth trochanter" for the attachment of the heavy coccygeo-femoral muscles (which were of great importance for the advancement of the body through the push of the hind legs) may be seen. The carpus and tarsus are imperfectly known, and probably were partly cartilaginous. The normal reptilian phalangeal formula of 2, 3, 4, 5, 3 appear to have been present.

[1] W. K. Gregory, and C. L. Camp, "Studies in Comparative Myology and Osteology," *Bull. Amer. Mus. Nat. Hist.*, Vol. XXXVIII (1918), p. 517.

[2] D. M. S. W. Watson, "Croonian Lecture, The Evolution and Origin of the Amphibia," *Phil. Trans. Roy. Soc.*, London, Ser. B, Vol. CCXIV (1926), pp. 189–257.

[3] Piveteau (*Bull. Soc. Geol. France* [4th ser., 1925], Vol. XXV, pp. 93–94) calls attention to the fact that reptiles, in general, have a neck, in constrast to the primitive amphibians, and attempts to use this as a taxonomic feature. But, as Williston states (*Contrib. Walker Mus.*, Vol. II [1917], pp. 51–52), "There is literally no neck in the cotylosaurs" and even the pelycosaurs (as *Ophiacodon* and *Theropleura*) are practically "neckless."

A life-restoration of *Seymouria* was published by Williston in 1914[1]. It will be noted that this is a lateral view, for which there was little information at that time, since the only skeletal restoration in existence was Williston's figure of the dorsal aspect. It is obvious from the model that this restoration is somewhat more "graceful" and the limbs much more slender than should be the case. The sketch given here (Fig. 4), prepared by Mr. Bruce N. Crandall, attempts to show the limbs in more of their proper proportions, with due regard to the musculature.

FIG. 4.—Restoration of *Seymouria baylorensis*. Drawn by Bruce N. Crandall, $\times\frac{1}{8}$, approx.

Seymouria and Conodectes.—In 1896,[2] eight years before Broili's description of *Seymouria*, Cope described *Conodectes* from the same beds, the type being a fragmentary skull. Williston, Watson, and von Huene have since recognized that the two are, in all probability, identical, and while the general disposition has been to regard *Conodectes* as a *nomen nudum*, Broom has recently pointed out that under the strict rules of taxonomy *Conodectes* must be used for this form. One of the main purposes of scientific nomenclature is (or should be) that of giving us a stable and universally intelligible set of zoölogical names instead of variable vernacular ones. But even among living forms "priority chasing" has brought us to the point where it is often necessary to use popular names to explain the mean-

[1] *Jour. Geol.*, Vol. XXII, p. 66.

[2] E. D. Cope, *Amer. Nat.*, Vol. XXX (1896), p. 398, and "Second Contribution to the History of the Cotylosauria," *Proc. Amer. Phil. Soc.*, Vol. XXXV, p. 129.

ing of "scientific" ones. It seems unfortunate to be required to extend such rules to fossil forms, where many of our older types are of a fragmentary nature; and it seems especially regrettable to be compelled to replace the well-known name of a morphologically important animal by one known to but a few specialists. *Seymouria* should be retained; and if this is in violation of "law," it is the rule rather than the name that should be changed.

Reptile or amphibian?—As noted above, *Seymouria* has usually been regarded as a very primitive reptile. But Broom in 1922 stated his belief that it is an advanced embolomerous amphibian, while more recently Sushkin has argued for its amphibian nature on the basis of the pterygo-quadrate complex and stapes.

Watson has discussed at length the evidence as to position, and many of the data need not be considered here. Most of the characters of the skeleton of *Seymouria* may be arranged in three categories: (1) features common to most of the primitive amphibians, not normally found in reptiles, but to be expected in an ancestral form under the reasonable hypothesis (developed by Watson) that the reptiles are to be derived from early embolomerous amphibians; (2) features found in both the Embolomeri and many primitive reptiles, but lost in the contemporary amphibians; (3) positive reptilian features, not normally found in amphibians of any group, as far as known.

In determining which side of the amphibian-reptilian boundary *Seymouria* is to be placed, only the characters of group 3 are relevant. These include (cf. Watson): (1) large ventral exposure of the basioccipital, (2) low position of the foramen ovale, (3) lack of external exposure of splenials below dentary, (4) unfused articular and surangular, (5) broad and swollen neural arches with horizontal zygapophysial surfaces, (6) complete true centra with considerable reduction of intercentra, (7) atlas-axis complex tending to reptilian type, (8) interclavicle with long posterior stem, (9) separate coracoid element, (10) entepicondylar foramen present in humerus, (11) phalangeal formula of 2, 3, 4, 5, 3. Few of these characters are known in any amphibian. A separate coracoid and entepicondylar foramen, for example, are found in Diplocaulus; but while this suggests interesting speculations as to the relationship of "nectridian" am-

phibians to the reptile stem, it does not detract from the reptilian nature of these features. The structure of the vertebrae is especially noteworthy; in fact, the form of the type of neural arches common to *Seymouria* and most other cotylosaurs is so characteristic that the writer has been inclined (perhaps incorrectly) to consider it as a cotylosaurian peculiarity not to be attributed to the ancestors of other reptiles; and that it should have been acquired independently by another group of embolomerous derivatives seems out of the question.

To offset these features and prove it an amphibian *Seymouria* and the embolomerous forms from which it is obviously derived must be shown to have structures which could not possibly have been present in an ancestor of the reptiles. Sushkin has essayed this task. His argument, as far as it concerns *Seymouria* and the Embolomeri, may, I think, be fairly summarized as follows:

1. In such a primitive reptile as *Captorhinus* the quadrate has a well-developed otic process, which articulates with the distal end of the parotic crest; this crest lies nearly horizontally and reaches the squamosal far laterally of its amphibian termination. The quadrate ramus of the pterygoid does not touch the squamosal, and does not form any definite postquadrate lamina. No otic notch is present.

   The Seymouriamorpha are not reptiles or ancestral to them. There is no otic process of the quadrate, which lies far laterally of the parotic crest. This is short, extends diagonally upward, and does not reach the squamosal. The pterygoid is in contact with the squamosal and has a large postquadrate lamina. There is a typical amphibian otic notch.
2. The same reasoning excludes the Embolomeri from reptilian ancestry. Further (*a*) their skulls are too large; amphibians tend to have large heads, reptiles have small ones, and the Embolomeri (and *Seymouria*) are large headed; (*b*) the amphibians tend to have a flattened skull (as seen in its proportions from behind), while reptilian skulls tend to be high and narrow; the Embolomeri (and *Seymouria*) have skulls of amphibian type.
3. The stapes furnishes a similar argument. In *Captorhinus* it extends laterally to articulate distally with the quadrate near the end of the parotic crest. In the Seymouriamorpha[1] the stapes extends diagonally upward, articulates

[1] The condition is known only in *Kotlassia*, an upper Permian form presumably related to *Seymouria*. In the specimen of *Seymouria* described by Williston, this region was excavated, at Dr. Sushkin's request, as far as could be done without serious injury to the specimen. No stapes was present in the captorhinid position; but it may have been present in a position similar to that of *Kotlassia*.

with the parotic crest and its osseous part ends at the otic notch, far from the quadrate. In the one described stapes of an embolomerous form conditions are similar, although there is some reason to believe that a cartilaginous branch may have articulated with the quadrate as well. This is the general amphibian condition, and is a morphological side line, for in most fish the hyomandibular complex (from which the stapes is derived) already articulates with the quadrate, and no reasonable explanation of the resumption of this condition when once lost can be made, even though it may have occurred in the ontogeny of forms lacking it in the adult condition.

These arguments may be considered in order.

1. The differences described appear to be entirely related to the presence in *Seymouria* of a typical otic notch, and its absence in *Captorhinus*. In *Seymouria* an otic process would be functionless, since the notch intervenes between quadrate and otic region. The parotic crest is necessarily short, since it must end proximally to the tympanic region and cannot reach the squamosal. The quadrate is placed far laterally in relation to the parotic region, but this is merely because the one does not extend inward nor the other outward (the skull proportions as seen from behind are similar). These extensions being absent, there is no interference with the apparently natural articulation of the pterygoid and squamosal, or with the development of a postquadrate lamina of the former. If we were to assume this condition to have been primitive, the entire elimination of the otic notch would seemingly result in the type of structure seen in *Captorhinus*.[1] The articular region of the jaw would be strengthened by the development of an otic process of the vertically placed quadrate, combined with a lateral shifting of the parotic crest into a horizontal position and a lengthening of that structure. This would naturally result in an articulation of the crest with the squamosal, and interference with the development of a squamosal contact of the pterygoid or postquadrate lamina of that element.

If, then, a typical otic notch is to be expected in the ancestry of the reptiles, there is nothing in the structure of the parotic region of *Seymouria* to debar that form from a morphologically ancestral position.

That such a notch was present there can be little doubt. With

[1] This series of probable changes has been, for the most part, discussed by Watson in various papers.

the loss of the opercular elements of the fish the spiracular slit, as seen in a rhipidistian crossopterygian or even in *Polypterus*, becomes indistinguishable from an otic notch; and the tympanic membrane which filled the notch is formed across a passage homologous with the spiracle. While in *Captorhinus* the notch has disappeared, other cotylosaurs, such as *Diadectes* and *Procolophon*, show it, although in a modified form which appears to be approximately intermediate morphologically between the fully developed notch and the position assumed by the tympanum in many modern reptiles.

No available evidence thus debars *Seymouria* from a position ancestral to reptiles as regards the structures discussed.

2. The same argument applies to the Embolomeri.

a) Further as regards size of heads, amphibians tend to have a large head, but while many reptiles have small skulls this also is a tendency only, and the actual figures do not support Sushkin's argument. It is impossible to obtain an absolute standard for the comparison of head size; probably the best figure that can be obtained is the ratio of head length to length of the vertebral column to the sacrum. Using published restorations as a basis,[1] the following typical figures are obtained: Rachitomi (moderately "advanced" amphibians): *Trematops* 74 per cent, *Cacops* 72, *Eryops* 59, *Trimerorachis* 38. Embolomeri (primitive amphibians): *Diplovertebron* 46, *Eogyrinus* 30, *Cricotus* 29. *Seymouria* 40. Cotylosauria (primitive reptiles): *Labidosaurus* 54, *Limnoscelis* 44, *Procolophon* 31, *Diadectes* 29. Pelycosauria ("advanced" Permian reptiles): *Ophiacodon* 52, *Dimetrodon* 47, *Varanops* 40, *Sphenacodon* 37, *Casea* 23, *Edaphosaurus* 18. In averages: Rachitomi 60.7, Embolomeri 35, Cotylosauria 39.5, Pelycosauria 34.5. The skull in the Embolomeri would thus appear to be smaller than that of the primitive reptiles measured, rather than too large, while *Seymouria* approximates the cotylosaur average. While the number of forms used is, of course, too small for such averages to be significant in a positive sense, they at least show the impossibility of proving the converse.

[1] These figures (and those under *b*) were taken, without conscious selection, from the papers nearest at hand at the moment. Almost without exception they are derived from Williston's papers in the *Walker Museum Contributions*, and Watson's two monographs on the evolution of the amphibia. While not complete they appear to be representative.

b) Again, while amphibian skulls are usually flattened and reptilian skulls high, these features are tendencies not well marked in primitive forms. Using the ratio of height of the skull table (above a line through the glenoids) to the width over all,[1] the following figures result: Stereospondyli (very "advanced" amphibians): *Cyclotosaurus* 29 per cent, *Batrachosuchus* 35, *Trematosaurus* 36. Rachitomi: *Lydekkerina* 26, *Eryops* 30, *Dwinasaurus* 40. Embolomeri: *Palaeogryinus* 40, *Orthosaurus* 40. *Seymouria* 39. Cotylosauria: *Pantylus* 30, *Limmoscelis* 31, *Labidosaurus* and *Captorhinus* 36, *Pareiasaurus* and *Procolophon* 39, *Diadectes* 70. Pelycosauria: *Casea* 32, *Varanops* 62, *Edaphosaurus* 76, *Sphenacodon* 88, *Mycterosaurus* 101. Averages: Stereospondyli 33, Rachitomi 32, Embolomeri 40, Cotylosauria 40, Pelycosauria 72. As far as such figures are significant, they suggest that the skull shape of *Seymouria* and the Embolomeri is exactly that which might have been postulated in an ancestor of the reptiles.

We need not seek forms with smaller heads or higher skulls for the ancestors of typical reptiles.

3. The argument that the position of the stapes in *Captorhinus* has been retained without change from the similar position of the homologous hyomandibular apparatus of the fish can be maintained only by a disregard of the function of the stapes.

The principal function of the homologous hyomandibular complex in fish is support of the quadrate region, and the "line" of this structure is naturally from braincase to quadrate. This function is lost in the ancestry of the tetrapods, and an entirely different one is assumed, namely, the transmission of sound waves from the tympanic membrane to the inner ear (within the braincase). We would expect the principal shaft of the stapedial complex to extend from the braincase (fenestra ovalis) to the region of the eardrum; and this is the case in every tetrapod with which I am familiar. The cartilaginous extrastapedial portion of the complex in living reptiles sends out various lateral branches, one of which attaches to the quadrate, but the osseous stapes always extends toward the eardrum and not toward any other region.

[1] A use of the height of the braincase instead of height from the quadrates might have given results somewhat more favorable to Sushkin's argument, but this figure is not available in many cases.

We would expect this relation to hold in a primitive tetrapod and an ancestral reptile. It cannot, I think, be doubted that an otic notch would have been present in such forms, and that the osseous stapes would have extended from the braincase[1] toward the tympanum situated in the notch.

This is the situation found in the Embolomeri and *Seymouria*. It is the one to be expected in an ancestral amphibian and, at some stage at least, in the ancestry of the reptiles.

Although the fact is of comparatively little functional importance, connections with the quadrate region may easily have been maintained. Watson believes a cartilaginous extension to have reached that bone in Embolomeri. Sushkin points out that in such a form as *Seymouria* the quadrate is at a considerable distance from the stapes and at right angles to its length. But the inferior process of the columellar apparatus of many reptiles extends to the quadrate at approximately a right angle and may equal or exceed the stapes in length.

In reptiles, however, the otic notch tends to be lost and the position of the tympanum shifts backward and downward. In *Diadectes* the modified notch is present, and Sushkin agrees that in this undoubted reptile the stapes (not found) extended into the notch rather than to the quadrate. In typical living reptiles the tympanum has shifted down to a position alongside the upper part of the quadrate, and the stapes has shifted downward in corresponding fashion. Its connection with the quadrate, because of juxtaposition, is often a short branch; but the osseous stapes extends toward the membrane, and not to the quadrate.

Captorhinus is assumed to be a morphological ancestor of the mammal-like reptiles, in which a greater ventral shifting of the membrane (to reach the angular region of the lower jaw) is occurring at a rapid rate. The tympanum is assumed to be in the region of the "glenoid," close beside the quadrate. To reach it, the stapes must pass very near the body of the quadrate; a connection of its osseous shaft with this element would appear to be a natural result.

The quadrate connection of the stapes in *Captorhinus* is inexplicable on the basis of its being the unchanged retention of the fish

[1] The question of the change in the principal braincase articulation is not pertinent to our discussion and need not be considered here.

condition. When interpreted functionally, it is evident that the condition of the stapes seen in *Seymouria* and the Embolomeri is necessarily intermediate. *Seymouria* cannot be debarred from the reptilian ancestry because of the probable condition of its columellar apparatus.

There are thus at present no valid morphological reasons for excluding *Seymouria* from the reptiles, or at least from a position ancestral to them. On the other hand, *Seymouria* possesses many positive reptilian characters. It thus seems to merit its accustomed position in that group.

One interesting speculative point remains. We have now reached the point (through the labors of Williston and Watson especially) at which it is impossible to draw any sharp morphological line of demarcation between amphibians and reptiles; our division must rest on embryological grounds, concerning which we have little to hope in the way of fossil evidence. The argument above has assumed that the cotylosaurs are not only ancestral to reptiles but actually members of that group. But it is possible (although perhaps not probable) that many of these forms (including *Seymouria*) may have still retained an aquatic larval condition, and thus have been, by definition, amphibians, although ancestral to the higher group.

Whatever the final disposition of *Seymouria*, the discussion only tends to emphasize its primitive character and morphological importance.

TEACHING VERTEBRATE PALEONTOLOGY

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ABSTRACT

This paper describes a method of teaching vertebrate paleontology. Because of lack of illustrative material for this subject in the small colleges, difficulties are often encountered. By letting the students make their own clay models of extinct vertebrates, the situation is improved.

INTRODUCTION

The teaching of vertebrate paleontology is admittedly no simple undertaking either in respect to the teacher's educational preparation, training, and experience or in the equipment at his disposal. He should be both a geologist and a biologist; a stratigrapher and an anatomist. The personal equipment is, however, far from all that is needed. No matter how well trained such a teacher may be, it is a difficult problem to present his topic in a manner to interest the student. Memory work based upon "dry" reading without concrete examples of the subject becomes an incubus. In most of our smaller colleges and universities, particularly in the eastern part of the country, collections of fossils, other than plants and invertebrates, are usually small or absent. Material is lacking for several reasons. Large expense is involved in purchasing or collecting backboned animal remains. Furthermore, such material fills space always at a premium about a geology department. It is sometimes possible for a class to visit one of the large museums where vertebrate fossils are shown, but these exhibits are often prohibitively distant. The same may be said of localities where materials may be collected for "home consumption." There are obtainable a limited variety of excellent plaster models of extinct vertebrates, but these leave unfilled gaps which no amount of lecturing can bridge satisfactorily.

Because of these limitations, the teacher of vertebrate paleontology in many institutions must have recourse to other methods. Textbook figures and accompanying descriptions are, to say the

least, unenlivening to the average undergraduate; technical descriptions of fossils are infinitely worse. Lantern slides may advance a step, but have the double drawback of inducing somnolence among the audience and producing a dearth of note-taking. The writer's own experience in teaching a semester of vertebrate paleontology has led him to adopt the method described in this paper.

METHOD OF TEACHING VERTEBRATE PALEONTOLOGY

The lecture system being in vogue, it became necessary to find illustrative material; and, furthermore, since laboratory work must be provided, to run parallel to the lectures, something had to be devised to fill those two hours a week. Fossil material in the collections amounted to a few specimens, mostly small or fragmentary, a series of representative skeletons of the classes of living vertebrates, some charts, mostly "home made," and a few of those plaster models which frequent every department of geology. Such material serves fairly well in lectures but is inadequate in the laboratory.

Additional laboratory work has been provided by requiring the students to make for themselves models of dinosaurs, mastodons, ostracoderms, and other forms out of "plasteline." This is a sort of modeling clay mixed with oil and admirably adapted to the work. A list of materials required may be instructive.

"Plasteline" of various colors
Wooden modeling tools and a few cheap kitchen knives
Several smooth, half-inch boards about 2 feet long by 1 foot wide to serve as bases for models
A spool of wire and a pair of pincers and wire-cutters
Wooden splints
Corrugated cardboard and string
One or two rolling pins
Several steel knitting needles

Each student selects some form of extinct vertebrate which is illustrated in one of the texts on vertebrate paleontology of historical geology. A figure which shows more than one aspect of the animal is greatly to be desired as giving better ideas of proportion. The models vary in size from six inches to a foot or so in length, the average being perhaps ten inches.

In going about the work, the two types of models found best

suited are the bas-relief and the statuette. In the case of the former, a lump of "plasteline" about the size of a man's two fists is kneaded and spread out on one of the boards in a layer perhaps half an inch thick. This is best done with the hands and a rolling pin. With the selected text figure before him, the student next draws upon the clay the outline of the animal, locating its more important features. A knitting needle makes an excellent stylus for this part of the operation. With a knife, the layer of "plasteline" is now cut out on the outline and the surplus around the edges removed. Next, with the knife, modeling tools, and needles, the surface is molded and

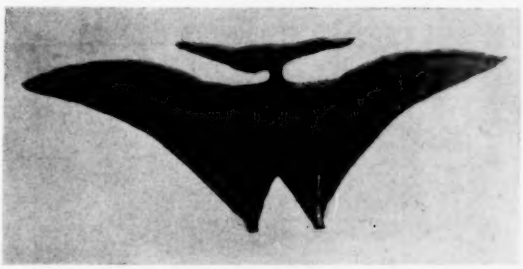

FIG. 1.—Bas-relief model of a pterodactyl (*Pteranodon*)

scraped until the desired contours are obtained. A pair of dividers is a help in determining comparative sizes of parts.

In making a statuette, more robust animals had best be selected, such as dinosaurs, elephants, marine reptiles, archaic mammals, and the like; fish, too, are satisfactory, especially since there are no legs, always a problem in construction. For the bas-relief, the more delicate forms are best, such as, for instance, the pterodactyl illustrated in Figure 1. In making the statuette, first the trunk is molded from a chunk of clay. In a large beast, such as a mammoth (Fig. 2), a roll of corrugated cardboard, smooth side out and tied with string, forms an excellent base when covered with a layer of "pasteline." This is quite satisfactory since it is firm, light, and conserves clay. In slender forms it is advisable to make a frame of wire and splints and lay the clay upon this. Splints are always necessary for the legs, since unbraced limbs have a faculty of weakening in warm weather and producing weird attitudes. The main parts having been united, body

contours are established by scraping, carving, and adding bits of clay. More than one shade of clay may be used for color effects; a good result was so obtained in the mammoth (Fig. 2), which is of brown clay with white tusks. Hair is simulated by making fine striations over the surface with a wire or knitting needle.

RESULTS OBTAINED

As an outcome of this method of teaching, a number of otherwise blank or partially used laboratory hours are filled. Each student produces one or more models and gains knowledge about that or those types. The general appearance of the other forms being

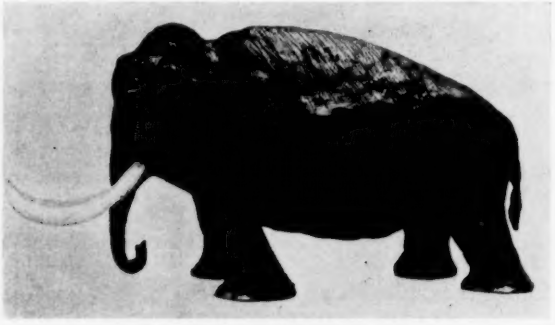

FIG. 2.—Statuette of a mammoth

constructed by the rest of the class is seen, for a certain amount of mutual interest and rivalry spring up. Reading and reports on the models further advance the student's understanding. Finally, he gains through touch valuable additional knowledge to sight.

But the advantages are not terminated in the gains made by the student who constructs a prehistoric beast from clay, nor with his classmates with whose several productions he makes comparison. The best restorations are available for future classes as illustrative material. Poor models—we are not all sculptors—are no loss of material since the clay may be re-worked many times. Finally, more enduring products may be made through running plaster casts from the clay models.

HISTORIC EVIDENCE ON CHANGES IN THE CHANNEL OF RIO PUERCO, A TRIBUTARY OF THE RIO GRANDE IN NEW MEXICO[1]

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ABSTRACT

The Rio Puerco, a tributary of the Rio Grande in New Mexico, has deepened and widened its channel, or arroyo, since the settlement of the region. This process of accelerated erosion still continues. Historical evidence, largely the notes and maps of government land surveyors, is cited to show that the cutting began between 1885 and 1890. The deepening of the arroyos has decreased the agricultural and grazing value of the country, resulting in the abandonment of six small towns and numerous ranches. The coincidence between the introduction of large numbers of stock and the cutting of arroyos indicates that overgrazing precipitated this form of destructive erosion. The ultimate cause, not completely discussed in this paper, appears to lie in cyclic fluctuations in climate.

INTRODUCTION

The Rio Puerco of the East, so called by the early explorers to distinguish it from a tributary of Little Colorado River of the same name, is one of the longest streams in New Mexico. Its length from its source on the west flank of the Nacimiento Mountains to its junction with the Rio Grande at San Acacia is 149.5 miles (Fig. 1). In the first 10 miles the flow is perennial or intermittent, but for the rest of its course it is a strictly ephemeral stream. Rains on the watershed are followed by muddy floods, but for long periods the bed is dry or contains stagnant and alkaline pools fed by ground water. The variation in flow is well shown by the records of a gaging station maintained since 1913 by the State Engineer[2] of New Mexico at the Santa Fe Railroad crossing. In the 13 years 1913–25 the annual discharge ranged from 3,280 to 229,000 acre-feet. The greatest

[1] Published by permission of J. L. Burkholder, chief engineer, Middle Rio Grande Conservancy District.

[2] George M. Neel, *Surface Water Supply of New Mexico, 1888–1925* (Santa Fe, 1926), pp. 287–90.

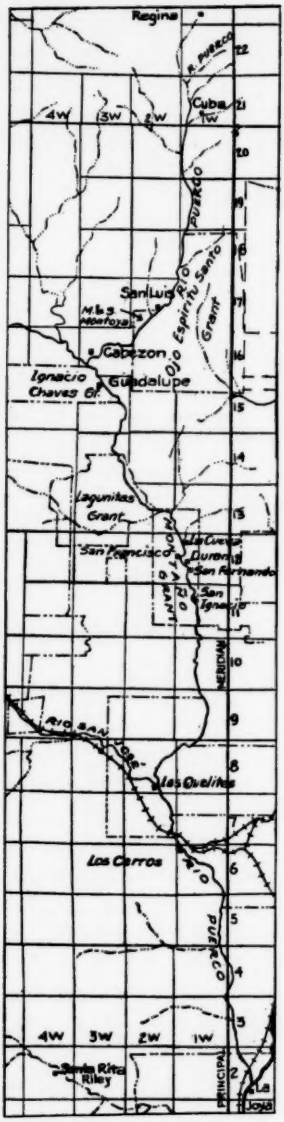

FIG. 1.—Map of the Rio Puerco, New Mexico.

flood recorded had a maximum discharge of 14,000 second-feet, but floods of twice this magnitude would doubtless be shown by a longer record.

Throughout its course the stream flows in a steep-walled gully incised in the valley floor. The valley floor varies in width from a quarter of a mile to three miles, and constitutes a terrace above the present stream grade. This terrace or abandoned flood plain is no longer overflowed, even by the largest floods. The present channel has an average depth of 28 feet and a width of 285 feet, which is more than ample, with existing grades, to accommodate floods much larger than have been observed. The channel is, therefore, a small gully and the river has, in common with other southwestern streams, begun a new cycle of erosion.

The general testimony of the older residents on the Rio Puerco is that the channel has deepened and widened within their memories. Oral tradition fixes this time of rapid deepening as the late eighties. Many testify that the river had no banks, or inconsiderable ones, and in flood spread over the whole valley floor; but the accounts of travelers indicate that at much earlier dates a considerable bank existed in certain localities. Before this study was begun, this discrepancy had been discovered and the need of additional and specific

information had been recognized.[1] The opportunity for renewed historical research on the date of channel trenching of Rio Puerco came during the past summer. George M. Post, formerly an engineer in the Indian Reclamation Service, and the writer made a study of erosion and the control of silt in Rio Puerco for the Middle Rio Grande Conservatory District. The present paper is the historical section of the unpublished report resulting from this study. The writer wishes to make grateful acknowledgment of assistance to Mr. Post and other engineers of the district.

The principal new materials used in this paper are the field notes of the early public land surveys which began with the survey of the New Mexico Principal Meridian in 1855. The notes and maps of these surveys are on file in the office of the district engineer of the General Land Office in Santa Fe, New Mexico, where the search for data was facilitated and every courtesy offered. All other available information has been used in order to obtain a true picture of the Rio Puerco as it once existed and an accurate story of the changes that have taken place.

In general, the early surveyors do not comment on the height of the banks, but they usually record the distance between them, either in the line of their survey or directly across the channel. Apparently the height of the banks did not impress the early surveyors, although at the present time the difficulties of crossing the channel with a line are so great as to induce comment by the most careless note-taker. Similarly, many of the early surveyors give the width of the water that chanced to be running at the time of the survey, or the width of the bed in which they considered that water ordinarily flowed. This practice may have been due to some preconceived idea, or it may be that the banks were so low as to have been thought unworthy of comment.

Generally, the width given in the notes is the distance from bank to bank in the direction of the surveyed line, rather than at right angles to the direction of the channel or the flow of water. There are

[1] Kirk Bryan, "Date of Channel Trenching (Arroyo Cutting) in the Arid Southwest," *Science*, n.s., Vol. LXIV (1925), pp. 338–44. On the same problem, see T. T. Swift, "Date of Channel Trenching in the Southwest," *idem*, Vol. LXIII (1926), pp. 70–71; Fred Wynn, "The West Fork of Gila River," *idem*, Vol. LXIV (1926), pp. 16–17; Kirk Bryan, "Channel Erosion of Rio Salado, Socorro County, N.M.," *U.S. Geol. Survey Bull. 790* (1927), pp. 15–19.

available for comparison cross-sections at right angles to flow made under the direction of George M. Post for the Middle Rio Grande Conservancy District in 1926 and 1927. These sections are not on the surveyed lines and give only an approximate comparison with the widths and depths recorded in the early surveys. A topographic map of the lower Puerco Valley, showing the position of the top of the bank, was also made by the Conservancy District in 1927. The data obtained by an intense but not exhaustive search of the records of the early government surveys have been assembled in Table I and compared with the recent surveys before noted. The material is arranged in order from the lower to the upper river, and is referred to in various parts of this discussion.

CHANNEL NEAR CABEZON

One of the best early accounts is that of Simpson,[1] who crossed the river in 1849, about 5 miles above Cabezon. He states that the channel was 100 feet wide; it contained stagnant pools of water; the banks were 20 and 30 feet high, and had to be cut down to allow passage of the artillery. Yet in spite of these high banks, changes in the position of channels have taken place in this vicinity which would have been impossible had the river not been flowing on the grade of its flood plain. At the south end of the M. and S. Montoya Grant, about 5 miles upstream from the town of Cabezon, the west boundary of the grant enters the channel of the river without crossing it. In the survey of this grant in 1877, Watts & Pradt report that this is a new channel with "high" banks marked by recent cave-ins and falling trees. They state that it lies west of the old channel which forms the eastern boundary of the grant. In resurveying this grant in 1899, G. H. Pradt, of the same firm, comments again on this change and gives the width of this new channel, where it is crossed by the east boundary, as 132 feet. In surveying the north boundary in 1877, Watts & Pradt begin on the west bank of the river, where the banks are "high," and run west without crossing the river; but Pradt, in 1899, begins at the same point on the west bank of the "old channel" and crosses the river which

[1] J. H. Simpson, *Journal of a Military Reconnaissance from Santa Fe, New Mexico, to the Navajo Country, etc.* (Philadelphia, 1852), p. 27.

TABLE I

TABLE I

MEASUREMENTS OF WIDTH AND DEPTH OF CHANNEL OF RIO PUERCO
COMPILED FROM SURVEY NOTES ON FILE IN UNITED STATES LAND OFFICE, SANTA FE, NEW MEXICO. CROSS-SECTIONS TAKEN UNDER DIRECTION OF GEORGE M. POST IN 1927 AND OTHER SURVEYS BY MIDDLE RIO GRANDE CONSERVANCY DISTRICT ARE GIVEN FOR COMPARISON

LOCATION OF LINE SURVEYED	T. 3 N., R. 1 W.									
	J. W. Garretson 1855		C. W. Devendorf 1920		R. A. Farmer 1922		George M. Post 1927		MIDDLE RIO GRANDE TOPOGRAPHIC SURVEY 1927	
	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Width (Feet) Normal to Channel
East boundary of Secs. 13 and 18	72.6 92.4	20	.....	30 or 40	399.9	25	‡450	‡42	450* 850*	Normal to channel Immediately south, 400–450 Immediately north, 320–50‡
	T. 4 N., R. 1 W.									
	J. W. Garretson 1855		D. R. Cunningham 1881		W. H. Richards 1912		George M. Post 1927			
East boundary of Sec. 12	132	.....	132	.....	452.5	30	.....	.....		
North boundary of Sec. 1	.....	.....	132	.....	.....	.....	.....	.....		
Line between Secs. 1 and 12	.....	.....	132	.....	.....	.....	‡325	‡30		
East boundary of Sec. 36	Line runs 250.8 ft. in channel without crossing		132	.....	788.7	25	‡440	‡34		
	T. 5 N., R. 1 W.									
	D. R. Cunningham 1881		William White 1897		Geo. H. Pradt 1898		J. H. Walker 1900			
North boundary, Sec. 1	99.0	.....	330.7	.....	.....	18	531.3	.....		
Line between Secs. 1 and 12	105.0	.....	410.5	.....	960.9	16	844.8	.....		
Line between Secs. 12 and 13	132.0	.....	.....	.....	.....	.....	.....	.....		
Line between Secs. 13 and 24	99.0	.....	.....	.....	.....	.....	.....	.....		
Line between Secs. 24 and 25	82.5	.....	.....	.....	.....	.....	.....	.....		
Line between Secs. 25 and 36	85.8	.....	.....	.....	.....	.....	.....	.....		
So. Bdy., Sec. 36	132.0	.....	.....	.....	.....	.....	.....	.....		

TABLE I—*Continued*

Location of Line Surveyed	T. 6 N., R. 1 W.											
	D. R. Cunningham 1881		William White 1897		Geo. H. Pradt 1898		J. H. Walker 1900		Geo. M. Post 1927		Survey of Rio Puerco Reservoir 1927	
	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)
North boundary of Sec. 6	132.0	.....	504.9	20	.....	.....	.....	.....	360	43	450	40
Line between Secs. 5 and 6	39.6	.....	186.1	20	.....	16	752.4	.....	480	40	900	.....
Line between Secs. 8 and 9	26.4	.....	374.5	.....	.....	18	143.9	.....	440	37	725	.....
Line between Secs. 9 and 16	66.0	.....	429.0	.....	.....	18	677.2	.....	440	33	800	.....
Line between Secs. 15 and 16	66.0	.....	264.0	.....	.....	16	299.7	.....	230†	46	325	.....
Line between Secs. 16 and 22	66.0	.....	.....	.....	.....	15	.....	.....	185†	30	.....	.....
Line between Secs. 22 and 23	99.0	.....	.....	.....	.....	15	.....	.....	250†	35	.....	.....
Line between Secs. 23 and 26	115.5	.....	493.7	.....	.....	15	797.94	.....	160†	43	625	.....
Line between Secs. 25 and 26	132.0	.....	653.4	.....	.....	18	665.3	.....	280†	42	550	.....
Line between Secs. 25 and 36	99.0	.....	863.3	.....	.....	14	559.2	.....	370	27	.....	.....
So. Bdy., Sec. 36	132.0	.....	330.7	.....	.....	18	531.3	.....	.....	.....	.....	.....

	T. 7 N., R. 2 W.			
	R. G. Marmon 1875–76		Geo. M. Post 1927	
North boundary of Sec. 2	198.0	.....	‡600	‡15

	Bernabe M. Montaño Grant									
	Sawyer and White 1877		H. T. Brown 1894		H. T. Brown 1896		Geo. M. Post 1927			
Unconfirmed south boundary near crossing on east boundary of surveys from 1894 to date	86.8 Bridge South 1,700 ft.	High	165.0	.....	.....	.....	‡130	‡37		
Unconfirmed west boundary near crossing of north boundary of surveys from 1894 to date	.....	Sandy banks	.....	.....	290.4	.....	‡210	‡15		

	T. 17 N., R. 2 W.			
	J. H. Walker 1906		Geo. M. Post 1927	
North Bdy of Sec. 1	297.0	15	‡110	‡8.5
Line between Secs. 1 and 12	198.0	.....	‡155.0	‡5.5
Line between Secs. 11 and 12	99.0	.....	‡98	‡18
Line between Secs. 11 and 14	92.4	.....	‡110	‡33
Line between Secs. 13 and 14	[illegible]	[illegible]	[illegible]	[illegible]

	T. 19 N., R. 1 W.
	[illegible]

Location of Line Surveyed	H. M. Neighbor and G. P. Harrington 1913		Geo. M. Post 1927									
	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)
T. 19 N., R. 1 W.												
South boundary of Sec 31	198.0	15	‡185	‡41								
T. 20 N., R. 1 W.	J. F. Thomas 1906		Geo. M. Post 1927									
South boundary of Sec. 31	183.5	10-16	‡145	‡15								
T. 16 N., R. 3 W.	A. F. Compton 1910		Geo. M. Post 1927									
Line between Sections 13 and 14	391.4	30	‡210	‡34								
Line between Sections 14 and 15	184.8	30	‡177	‡35								
Line between Sections 15 and 16	214.5	25	‡340	‡35								
M. and S. Montoya Grant	Pradt & Watts 1877		G. H. Pradt 1899		J. H. Walker 1906		Glenn R. Haste 1922		Geo. M. Post 1927			
North boundary	No new channel	High	New channel 198	.....	New channel 224.4	20	.....	.....	98	22		
West boundary	New channel reported 495.0	.....	495.0	.....	.....	.....	.....	.....	But 1.2 miles downstream 342	35		
East boundary Near SE. corner	.....	High	231 (true width is 132)	.....	.....	.....	.....	.....	215	35		
Near NE. corner	.....	.....	99	.....	.....	.....	.....	.....	.....	.....		
West boundary of T. 16 N., R. 2 W. at Sec. 18, about 1 mile downstream from above (calculated width of river)	.....	.....	.....	.....	.....	.....	1,384.5	.....	207	30		

TABLE I—*Continued*

Location of Line Surveyed	Nuestra Señora de la Luz de las Lagunitas del Rio Puerco Grant											
	S. C. McElroy 1877		J. H. Walker 1901		Miller & Lyman 1915		Geo. M. Post 1927					
	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)	Width (Feet)	Depth (Feet)
North boundary	‖26.4	High	.....	.....	823.8 165.0	30 40	‡110	‡18				
Southeast corner	‖79.2	High	138.6	.....	.....	.....	‡210	‡15				
	T. 15 N., R. 3 W.											
	J. W. Walker 1906		Geo. M. Post									
South boundary of Sec. 35	405.9 Records river change since earlier survey by shift to the east	10–15	‡212	‡18								
	Ignacio Chaves Grant											
	Pradt & Watts 1878–79		A. F. Easley 1879		A. F. Compton 1910		Geo. M. Post 1927					
Preliminary east boundary. This line crosses at small angle bridge 400 feet south	733.9	.....	.....	.....	.....	.....	.....	.....				
North boundary	.....	.....	175.0	8	735.9	30	‡240	‡30				
South boundary	145	High	167.6	15	.....	.....	‡132	‡41				

* In line of survey.

† In narrow places; wider places are 1,000 feet or more.

‡ Nearest cross-section.

§ San Luis diversion dam, a structure of logs and brush, holds river channel to or above original depth in this area.

‖ Measurement may refer to water in the channel, and not to channel.

occupies a "new channel," 198 feet wide. J. H. Walker, in 1906, found that this "new channel" was in the same location and was 224.4 feet wide and 20 feet deep. These surveys establish considerable lateral shifts of the river channel, which took place in spite of its high banks, and were, as will be seen, in part induced by the activity of settlers.

Meliton Cordova, now a resident of Albuquerque, went to Cabezon about 1870, when he was a small boy. The flood plain of the Puerco was without a deep channel. There were large groves of cottonwood trees and high grass and weeds. It was necessary for the settlers, in order to find the cattle, to climb the hills and look down into the valley. There was a bridge over the river, but it was small, such as is used to cross an *acequia*, or irrigating ditch, in the Rio Grande Valley.

One man could build a dam for diverting the river by felling a cottonwood tree across the channel and using the branches to fill in the chinks of the dam. The dam at San Luis was built about 1875, but it was then a very small affair of brush and poles. The river washed around it during a flood and this caused the channel change, recorded in the surveys of the north boundary of the Montoya Grant by Watts & Pradt (1877) and Pradt (1899). Similarly, the channel change at the lower end of the Montoya Grant, recorded in the survey of Watts & Pradt of 1877, was caused by the activity of William Kensenbach, a settler, who in that year diverted flood waters from the hills into a line of little ponds and depressions on the west side of the valley. Thus a channel was begun, and when a flood on the Rio Puerco washed around the Cabezon dam, which lay upstream, the waters enlarged this channel and made it permanently the channel of the river.

Don Amado Chaves, now a resident of Santa Fe, crossed the Rio Puerco frequently during several years after 1876 on the road from Santa Fe to San Mateo by way of Cabezon. During this period the river channel was shallow and the bottom was corduroyed with large logs so as to make the muddy bottom passable for carriages. These logs were occasionally washed away.

Restituto Sandoval, a resident of Cabezon, visited the place first as a boy of thirteen, in 1882. There was then a small bridge over

the river, not over 5 feet high. When he returned the next year to take up permanent residence this bridge was useless, for in the meantime the channel had changed position. It seems likely that it was such a bridge as this which Jackson[1] crossed in 1877. According to Don Amado Chaves, a corduroy was also used at this time. These small structures were not intended to make the valley passable during great floods, which, according to Restituto Sandoval, spread over the banks of the channel and covered the whole valley. Overtopping of the banks at Cabezon is now impossible and has been since before 1910, for the channel was then about 35 feet deep and a veritable canyon, as shown by the subdivision survey and plot of T. 16 N., R. 3 W., made by A. F. Compton in that year. After the deep channel was cut, a well at Sandoval's house went dry and was abandoned. At the present time he and the other inhabitants of Cabezon must haul water from a small reservoir 3 miles west. He believes that the river cut down and the well went dry between 1885 and 1890.

Meliton Cordova moved away from Cabezon in 1900, because he could no longer cultivate successfully and the town was not prosperous. He believes that the channel began to get deep about 1890 to 1892.

About 10 miles below Cabezon, J. W. Walker, in surveying the south boundary of T. 15 N., R. 3 W., in 1906, found a channel 405.9 feet wide on the line of his survey, and with banks 15 feet high. It was not in the position of the river bed given by earlier surveys, where, however, he found a depression trending NE. and SW. His notes state that this is the former position of the river, as old settlers tell him that the river once spread over the entire valley and that the present bed has been formed since the earlier surveys.

Meliton Cordova, previously mentioned, says that there was always a well-defined channel below the "Salta" or rock falls at Guadalupe, that is, in the area surveyed by Walker. However, above Guadalupe the channel was insignificant. This is confirmed by the statement of Alcario Montoya, who crossed the Puerco at Guadalupe

[1] W. H. Jackson, "Report on the Ancient Ruins Examined in 1875 and 1877. Chapter II, Ruins of the Chaco Canyon Examined in 1877," *U.S. Geol. and Geogr. Surveys. Terr.* (Hayden Survey), 10th Annual Report (1878), p. 432.

in 1887, and remembers that the channel was about 3 feet deep and 30 feet wide. These statements may be compared with data given by early surveys of the Lagunitas Grant, on which Guadalupe is located. McElroy, in 1877, gives the width of the river as 26.4 and 29.2 feet at the north and south boundaries of the grant, but his notes are not clear as to whether this distance is from bank to bank or merely the width of the water flowing at that time.

Above Cabezon, early surveys that give the width and depth of channel have not been found, but in T. 17 N., R. 2 W., deepening and widening of the channel since 1906 is shown, except where the San Luis Dam has raised the stream grade. According to Epitacio Salas, who was born in La Ventana in 1874, the channel there, when he was a boy, was about 8 feet deep, whereas now it is 40 feet deep. There was a small channel at Cuba; but midway to La Ventana and opposite La Vega de China, where the Señorito and San Pablo creeks enter the river, the valley floor of the Puerco was a smooth plain. He remembers this fact because as a boy he crossed the river with a band of ewes.

CHANNEL IN THE MONTAÑO GRANT

Further south, on the Montaño Grant, Abert[1] reached the Rio Puerco in 1847 at a point west of Albuquerque, where the banks were "10 or 12 feet high" and vertical. He must have arrived at the Puerco near the site of San Ignacio, which did not exist at that time, and he camped farther upstream near a ruined town which he heard afterward was called "Poblazon," and here the banks of the river were 30 feet high.

On the map resulting from their survey of 1877, Sawyer and White show four towns on this grant: La Cueva, on the east bank, with three houses (in Sec. 7, T. 12 N., R. 1 W., projected); San Francisco, on the west side of river, with four houses (in Sec. 18, projected. This is in error, for in 1909 there were ruins of ten or fifteen houses); Duran, with three houses (at corner of Secs. 19 and 20, projected); San Ignacio, on east bank, with eight houses (in Sec. 9,

[1] Lieutenant J. W. Abert, "Report of His Examination of New Mexico in the Years 1846–47," *Ex. Doc. 41*, 30th Congress, 1st Sess. (1848), pp. 466–67; also printed as *Sen. Ex. Doc. 23* (1848), pp. 50–51.

T. 11 N., R. 1 W., projected; more houses in 1909). They credit San Francisco, also called Ojito, with more than 100 inhabitants, and San Ignacio, also called Atarque, with 150 inhabitants.

H. T. Brown surveyed the grant in 1894 and in 1896. In his notes he describes the ruined town of Nuestra Señora de la Luz San Fernando y San Blas del Rio Puerco as situated on the east side of the river, midway between San Francisco and San Ignacio, near the point of the Mesa Baptiste (Bautista). The ruins covered an area of 330 by 400 feet, and were seen by me in 1909. According to contemporary legal documents, this town[1] was settled by twelve families in 1753, occupied for 20 years, and abandoned because of hostility of the Indians. Brown notes that San Francisco and San Ignacio were nearly deserted in 1894. In 1896 work was being carried on in the building of dams and other works of the English company which attempted to irrigate the grant at this time. After the failure of this project San Francisco was deserted, and even the memory of La Cueva and Duran was lost. San Ignacio, reduced to about fifty people, persisted until 1911, but practically no farming was carried on, the inhabitants living by stock-raising and freighting. At that time the owners of the grant bought the improvements and some of the people settled west of the grant at Ojo Hediondo, where the post-office of San Ignacio is now located.

CHANNEL SOUTH OF SANTA FE RAILROAD

South of the Santa Fe Railroad the banks were, according to statements of early residents, generally low. However, J. W. Garretson, in running the Principal Meridian, gives the height of the banks as 20 feet and the width 132 feet where he crossed the river in Sec. 13, T. 3 N., R. 1 W. In Figure 2 the channel recorded by Garretson is compared with the topographic map of the Middle Rio Grande Conservancy District. At his crossings in the next township north he does not mention the height of the banks. D. R. Cunningham, who subdivided Townships 3, 4, 5, and 6 N., R. 1 W., in 1881, does not give the height of the bank, but records a channel from 1 to 2 chains (66 to 132 feet) wide. These are, undoubtedly, merely estimated

[1] R. E. Twitchell, *The Spanish Archives of New Mexico*, Vol. I (1914), pp. 90–92 *et al.*

widths, but the most careless surveyor could not estimate the present channel as so narrow. The later surveys in this vicinity also show a progressive widening and deepening which began after 1881. That the river in places had a shallow channel in 1881 is also indicated by a lateral shift, or new channel, recorded in the survey of T. 6 N., R 1 W., and by Cunningham's note: "Water taken from the river

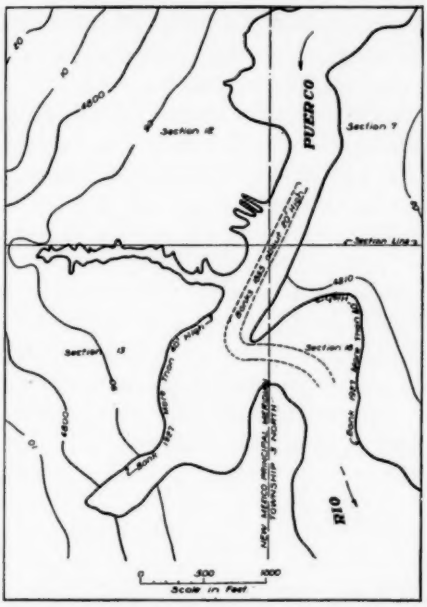

FIG. 2.—Map of the channel of Rio Puerco in T. 3 N., R. 1 W., as surveyed in 1927, and channel recorded by Garretson in 1855.

for irrigation near village of Los Cerros in Section 6. Village has 50–60 inhabitants who cultivate land in Sections 5, 6 and 8." Remnants of a brush and rock dam used for diversion were found in 1927 by Mr. George M. Post, about 2 miles south of the A. T. & S. F. Railway, and therefore in a suitable place to divert water for the lands at Los Cerros. The base of the remnant of this dam is, according to a measurement by Mr. Post, 22 feet above the bottom of the 1927 channel of the Rio Puerco. This dam, according to local people,

was in use as late as 1887. For instance, Fred F. Chavez, of Albuquerque, remembers going to Los Cerros to hoe corn when he was a boy of eleven, or in 1886. As late as 1895 or 1896 he remembers, on a trip to the west from Belen, that he saw corn growing at Los Cerros; but he believes that it was irrigated by flood water from the hills, as he remembers that the dam washed out when he was still a boy. Evidently the deep channel of the Rio Puerco worked headward into this area, requiring a substantial diversion dam in the later years of occupation, but when this structure washed out, the people became discouraged and abandoned the town of Los Cerros. Thus the river had a shallow, narrow, and shifting channel as late as 1881, and diversion was possible as late as 1887; but 20 miles to the south, 20 foot banks, as recorded by Garretson, characterized the channel as early as 1855.

REVIEW OF EVIDENCE

A review of the evidence presented in the foregoing and in Table I indicates that the earliest records prove definitely that at places the Rio Puerco had banks as high as 20, and even 30, feet. At other places the banks were so low and inconspicuous as not to be recorded. In floods, most of the valley floor was inundated, and in those years good crops of wheat, corn, and beans were raised. Natural hay fields in the valley floor or in the tributary valleys were irrigated by these overflows, and the hay cut was hauled to Albuquerque as late as 1895. One large livery stable used regularly about 10 tons a month. These hayfields are recorded in place names such as Vega Quelites, at the mouth of San José River, Vega Verde, just south of Ojito, on the Montaño Grant, and La Vega de la China, between Cuba and La Ventana.

During the inundations of the valley floor the river channel might shift materially. Some of these shifts north of Cabezon, as recorded by the successive surveys, are of artificial origin. Others, of doubtless more ancient date, are recorded in this area by numerous corrugations of the valley floor. These abandoned channels are 2–10 feet deep and 25–150 feet wide. In them once lay the pools of water which old settlers call *lagunitas*, a name perpetuated in the Lagunitas grant.

Deep and fairly stable channels were doubtless formed at certain localities. The entrance of large tributaries, narrowness of valley floor, and other factors determined the location, size, and the period of duration of these channels. The Rio Puerco was, previous to the late eighties, an ephemeral stream of great length, subject to numerous floods of short duration, but occasionally of great magnitude. It flowed in a flood plain subject to overflow and had a discontinuous channel. The discontinuity of the channel affords a rational explanation of the otherwise conflicting historical evidence on the character of the valley and its watercourse.

The new deep channel was formed from the mouth headward. Thirty-four miles above the mouth, Los Cerros was abandoned about 1887. San Ignacio, 62 miles, and San Francisco, 73 miles, were nearly abandoned in 1894, and the channel doubtless deepened some years before, as the nearby La Cueva and Duran were already abandoned. The deep channel reached Cabezon, 110 miles from the mouth, between 1885 and 1892. It is, therefore, fair to say that the cutting of the existing deep arroyo on the Rio Puerco took place in the late eighties, although the completion of the work and the extension of the arroyo headward into the tributaries is still in progress.

QUANTITY OF MATERIAL ERODED

As a result of surveys made by George M. Post for the Middle Rio Grande Conservancy District, the cubic volume of the present channel of the Rio Puerco and the channels of its tributaries can be estimated. The volume of the original channels can be estimated from the historical data hereinbefore presented. The original channels were less than 5 per cent of the existing channels. Mud and silt have been swept out of the Rio Puerco into the Rio Grande in the past 42 years to the amount of 394,882 acre-feet, or at an average rate of 9,400 acre-feet a year.

OVERGRAZING IN RELATION TO THE DEEPENING AND WIDENING OF ARROYOS

It has long been contended that the decrease in vegetative cover brought about by the introduction of live stock promotes run-off.

The more rapid run-off increases the magnitude of floods and the erosive and transporting power of streams. The Indians of pre-Spanish days lacked domestic animals, except the dog, although they kept and herded in the fields large numbers of turkeys. Herbivorous live stock were introduced by the Spanish, who first entered the region in 1540,[1] but did not found settlements until Oñate's Conquest, in 1592. For some time later the Puerco watershed was largely Indian country. It appears that settlement did not take place until the latter part of the eighteenth century.[2] These settlers were continuously harassed by Navajo raiders and were ordered to retire to the Rio Grande Valley in 1823 for lack of military protection. The number of live stock grazed in the area by these people was doubtless small, although the inhabitants of the Rio Puerco north of Cabezon claimed to have 10,000 head of cattle at this time.[3] Even after they left, some live stock were kept in the area, for we know from Pattie's narrative and other contemporary sources that the Navajos maintained both horses and sheep before 1825. After several ineffective campaigns the Navajos were finally conquered in 1865. Settlement was begun in the seventies, and efforts were made to have the Spanish grants confirmed as evidenced by the surveys of 1877–79, already mentioned. The country was not fully stocked with cattle until after 1880. As brought out on p. 274, destructive erosion followed promptly in the period 1885–90.

The time relations are thus favorable to the claim that overgrazing is the cause of arroyo-cutting. There must have been, however, a very nice adjustment of climate so that sufficient vegetation would grow to prevent erosion, but not so much but that the reduction of that vegetation by grazing would precipitate destructive erosion.

[1] R. E. Twitchell, *Leading Facts of New Mexico History*, 5 vols. (1911 and later).

[2] In R. E. Twitchell, *Spanish Archives of New Mexico*, Vol. I (1914), note claims of Joaquin Mestas, 1762–68, on pp. 159–60; M. and S. Montoya grant, possession given 1766, on pp. 161–62; Lagunitas grant, first given to Antonio Baca in 1761, on p. 41; Montaño grant, given in 1753, inhabited 20 years, pp. 90–92; litigation, 1753–59 and 1767, on p. 189; 1767, on p. 162; 1770, on p. 83; Agua Salada grant, given to Luis Jaramillo, 1769, on p. 128; Los Quelites occupied by Antonio Sedillo, *cerca* 1762–66, on p. 70.

[3] R. E. Twitchell, *ibid.*, p. 41.

On Chaco River,[1] a similar stream some 70 miles northwest, an arroyo has been cut since 1860. Previously, however, an arroyo similar to the modern arroyo was formed in late prehistoric time. This channel was filled with alluvium and the floor of the valley once more became a true flood plain. Obviously the erosion of this prehistoric arroyo could not have been brought about by overgrazing. On Rio Puerco a similar ancient arroyo, completely filled by renewed sedimentation, has been discovered. No human relics by which its age might be determined have been found, but it is similar in appearance to the buried arroyo of late prehistoric date in Chaco Canyon. Thus on both of these streams cyclic changes from sedimentation to erosion and back to sedimentation took place before the introduction of live stock and the formation of the existing arroyos. It appears inherently most probable that these cyclic changes have a common, and doubtless a climatic, cause. The introduction of livestock and the ensuing overgrazing should be regarded as a mere trigger pull which timed a change about to take place.

CONCLUSION

Historical evidence is presented which shows that on the Rio Puerco there existed before 1885 a small channel that in places had banks 10–20 feet in height and in other places was insignificant. Floods spread over the valley floor, which was a true flood plain. From 1885 to 1890 the channel was deepened and widened, a process still continuing on both the river and its tributaries. The valley floor has been abandoned as a flood plain.

The effect of this destructive erosion on agriculture and grazing has been disastrous. Six towns have been abandoned, and some of the remaining settlements have been impoverished. Silt to the amount of 9,400 acre-feet a year has been poured into Rio Grande Valley. It has choked the channel of that river and increased the damage from flood. A large proportion of this silt has been carried into Elephant Butte Reservoir, and reduces the storage space for water. As arroyo-cutting progresses, flood damage and loss of stor-

[1] Kirk Bryan, "Recent Deposits of Chaco Canyon in Relation to the Life of the Prehistoric Peoples of Pueblo Bonito" (abstract), *Wash. Acad. Sci. Jour.*, Vol. XVI (1926), pp. 75–76.

age will continue. The prevention of further cutting by the arroyos and the restoration of the stream channels to something like their pristine condition is a practical problem of large importance. Rehabilitation of the Puerco watershed seems feasible from both the physical and economic aspects, but discussion of these matters lies outside the scope of this paper.

The deepening and widening of the channel of Rio Puerco is an example of changes in the channels of ephemeral and intermittent streams which have been coincident with settlement and the introduction of live stock throughout the Southwest. The ultimate cause of these changes can only be completely evaluated by means of careful historical study.

COMPARATIVE COLOR RATIOS OF AMERICAN AND EUROPEAN ROCKS

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ABSTRACT

North American igneous rocks are shown to be universally lighter in color (and therefore also in density) than European rocks of the same kind. Curves are given showing this color difference for granites, granodioritic-granites, rhyolites, gabbros, and basalts. Since an insufficient number of modal analyses is available, use was made of the ratios of light to dark minerals in the norm, for this ratio is practically the same as the ratio in the modes.

In the preparation of the manuscript of a forthcoming *Descriptive Petrography*, many rocks were classified according to their mineralogical compositions, and the curious fact appeared that the various kinds of rocks in the United States are much lighter in color, and therefore also in specific gravity, than foreign rocks of the same kind. Unfortunately the total number of modal analyses found in the literature does not exceed two thousand for all classes of rocks, and the number of any one kind of rock is not great enough to carry out the comparison as far as is desirable. Since it was desired simply to compare the percentages of dark minerals in rocks of North America with those in rocks of similar composition in Europe, it was possible to make use of the ratios of femic (omitting apatite) to salic minerals in the norms, as calculated from chemical analyses. These values for color are not far different from the ratios of actual dark to light minerals in the mode, in spite of the fact that generally the normative minerals differ from the modal minerals in kind and amount.

The calculated norms in Washington's tables[1] were used. Since it is impossible to depend upon the published names of rocks for their true classificatory positions (the granodiorites of one writer being the granites of another and the quartz-monzonites of a third) it was thought best (though probably unnecessary) to select the so-called granites, gabbros, etc., on the basis of the calculated norma-

[1] H. S. Washington, "Chemical Analyses of Igneous Rocks," *U. S. Geol. Survey P.P. 99*, 1917.

tive minerals. That such a selection was made is a matter of little importance, however, since the rocks of America and the rocks of Europe were selected on the same basis. Since all the rocks of like composition were taken, regardless of the normative families under which they were classified, there was no question of a "personal equation," more especially since no comparison could be made until the rocks were plotted. The comparison thus has the same value as would a comparison of the actual modes.

The rocks called granites in Washington's tables were divided into two groups, since it would obviously be unfair to compare granite of normal composition (with orthoclase greater in amount than plagioclase) of one region with such rocks as quartz-monzonite or granodiorite of another. The latter rocks, with the increase of plagioclase, normally contain also more mafic minerals. In the first group, called "granites" in the figure, those rocks were taken whose norms showed more orthoclase than albite plus anorthite. Certainly most of these rocks are actually granites of Family 226 of the writer's classification. In the second group those so-called granites are included whose orthoclase in the norm is less than the sum of albite and anorthite. Most of these rocks are of Family 227, but some are undoubtedly soda-granites of Family 226, since some of the soda may be present in orthoclase as microperthite, or they may belong to 216, with sodaclase as the principal feldspar. Many of the rocks are granodiorites.

The definitions of gabbro and basalt are practically the same everywhere, although a few writers still consider gabbro necessarily a pyroxene rock, and basalt one containing olivine. The writer regards the presence of basic plagioclase as the essential, and in the selection of rocks for these curves it was only necessary to discard those in which albite in the norms exceeded anorthite. These normative percentages may not quite represent the modes, but in the case of gabbros and basalts, which contain no orthoclase, the values are not far wrong.

Since there are not the same number of analyzed rocks for North America and for Europe, to make the curves comparable it was only necessary to make the horizontal scales of the two of the same length and divide them into as many parts as there were analyses. Beginning at the left with the rock having the highest percentage

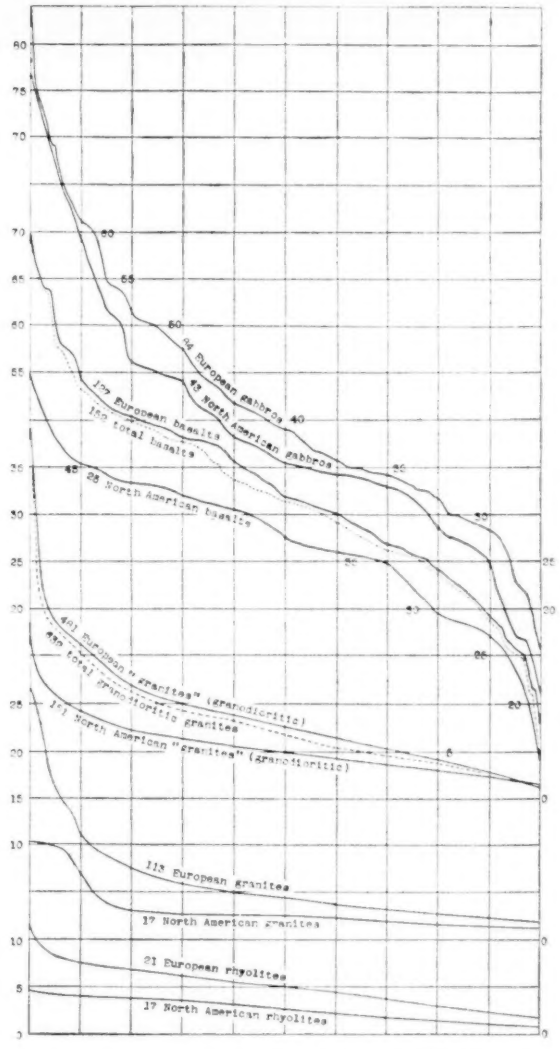

FIG. 1.—Curves illustrating the relative amounts of dark constituents in the rocks of North America and Europe. Abscissas represent the percentages of dark minerals.

of dark minerals, at each successive point the abscissa represents a rock with a lower mafic percentage. Curves based on a few rocks are angular, but with an increased number of specimens the curve smooths out. As may be seen, in every case the curve for America lies below that of Europe, indicating that the European rocks are darker in color than the corresponding ones from America. Only in the case of the granodioritic-granites is there a crossing of the line. Here, near the right end, the American curve crosses, but this simply indicates that among the determined rocks there happened to be a few of lighter color from Europe than the lightest from this country. A very few lighter rocks from the United States placed at this end would throw the curve below. Such rocks did not happen to be among those chosen, possibly because in this country these lighter-colored ones were classed as alaskites, and the rocks chosen for the curve were only those called granites.

A comparison of the actual modes of all classes of rocks, as far as the numbers of modal analyses go, shows the same leucocratic character in all those from America.

An attempt was made to compare the "granodioritic-granites" of the Pacific coast with those of the Atlantic. This gave a curve which crossed four times in the left third, but only 21 west-coast rocks as against 112 east-coast were found. To the right of the last crossing, the west-coast rocks remained about 1 per cent below the east coast, but there are not enough determinations to indicate definitely that the west-coast rocks are lighter.

Several years ago Washington[1] determined the average density of the igneous rocks of various regions. He calculated the average chemical composition of the rocks, and from this calculated the norm. Knowing the densities of the normative minerals, it was possible to calculate the average density of the rocks. He thus found that the average density of the igneous rocks of a region varies inversely as the average altitude. He also showed that the average of all European rocks is heavier than the average of all American. In the present paper it is shown that each *kind* of rock in North America is lighter in color (and therefore also in weight) than the *corresponding rock* in Europe.

[1] H. S. Washington, "Isostasy and Density," *Bull. Geol. Soc. Amer.*, XXXIII (1922), 375–410. F. W. Clarke and H. S. Washington, "The Composition of the Earth's Crust," *U.S. Geol. Survey P.P. 127*, 1924.

REVIEWS

The Founders of Seismology. By CHARLES DAVISON. Cambridge University Press, New York: Macmillan Co., 1927. Pp. 240, figs. 11. 12s. 6d; $4.25.

The birth of seismology, according to Davison, dates from the middle of the eighteenth century, "from the time when those who studied earthquakes drew their illustrations from contemporary records and no longer from the writings of Aristotle, Seneca, or Pliny. From this point of view, the first founder of seismology would be John Michell (1724–93)." The period of eighty years (1760–1840) produced no outstanding figure in seismology, though it was a time of steady growth in earthquake knowledge. Then came Alexis Perry (1807–82) and Robert Mallet (1810–81), to each of whom a chapter is devoted. The next three chapters treat, respectively, the study of earthquakes in Italy, in Central Europe, and in the United States, while the final three chapters are devoted to three outstanding seismologists of very recent years—Montessus de Ballore Milne, and Omori.

Most of the biographical chapters are not merely life-sketches of the selected central figures, but the inclusion of much of the contemporaneous development of seismology gives the proper background for the lives and works of the master-founders. The book is very readable and interesting, and gives an excellent account of the development of the science of seismology.

R. T. C.

Varve Materials and Banded Rocks. By R. C. WALLACE. *Transactions of the Royal Society, Canada,* Vol. XXI (1927), Sec. 4, pp. 109–18.

The present study deals with the relative mechanical and chemical composition of the varve materials. Chemical analyses of Pleistocene varved clays from Don Valley, in Toronto, Cross Lake in eastern Manitoba, and Herb Lake in northern Manitoba show particularly that the summer layers are richer in lime, and the winter layers richer in alumina, ferric oxide, and potash. Mechanical analyses reveal that the Winnipeg Basin clays have an exceptionally high percentage of fine material which is distributed throughout the varve. They also show that the Don Valley clays and Cross Lake clays have the clay and silt particles distinctly sepa-

rated, the former occurring preponderantly in the winter layers, the latter in the summer layers.

Wallace has also examined under the microscope specimens of the varved Middle Huronian slate at Cobalt in Ontario and of the Permo-Carboniferous argillite at Squantum, Boston. The Cobalt rock is a consolidated arkose-like greywacke, unweathered and with angular grains. The material was a rock flour. The consolidation has taken place without silification, without change in the grains, and almost without crystallization. The specimen examined is very thinly varved. The coarse material is of a very uniform grade. Scattered throughout the fine material there is a considerable percentage of coarse grains, in part in layers.

The Squantum rock, which differs fundamentally from the Cobalt rock, was originally composed of clay. It is very fine grained. The coarser grains consist of quartz and feldspar and are mostly angular. The varvity is somewhat indefinite, particularly under the microscope. The varves are thin. The fine layers contain coarse grains, mostly irregularly distributed.

The study shows that the Cobalt slate was formed of freshly broken unweathered rock flour such as is best produced by glacial erosion. The material of the Squantum slate had reached a greater degree of weathering and, judging solely from the microscopical investigation, is not conclusively glacial, though the nature of the larger fractured grains might suggest that origin.

The layers of coarse grains in the winter zones can be explained if the lake was not covered by ice in the winter months, or if a sudden influx of water, due to higher temperature, brought coarser material into an ice-covered lake from time to time. This latter explanation was also forwarded by R. W. Sayles. In either case there must be postulated higher temperatures than during the retreat of the ice in Pleistocene times. This is another promising use of varves as climatic indicators.

ERNST ANTEVS

Water Resources of Missouri. By H. C. BECKMAN. Missouri Bureau Geol. and Mines, Vol. XX, 2d Series, Rolla, Missouri, 1927. Pp. 424; pls. 12; map; 19 figs.

This bulletin is a complete compilation of records on the flow and chemical content of Missouri waters. The main part consists of tables of the flow of streams by months, and descriptions of the various drainage basins of the state. There are also chapters on springs, drainage areas, chemical analyses of surface waters, and bibliography.

C. C. B.